First observation of the B_c^+ meson in PbPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with CMS

Guillaume Falmagne
Laboratoire Leprince-Ringuet, Palaiseau (France)

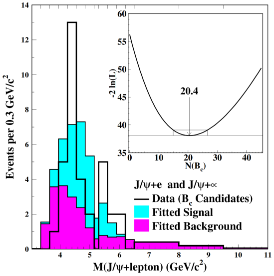
CERN-LHC seminar
July 20th, 2021

Main results from
CMS-PAS-HIN-20-004

B_c^+ in pp and $p\bar{p}$ collisions

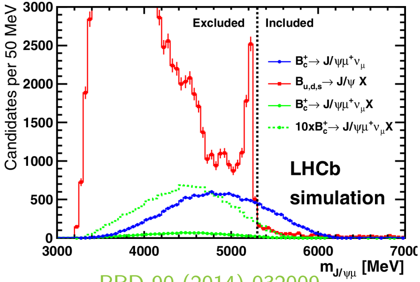
- B_c lifetime 3× smaller (150 μm) than B
- B_c cross section is small: needs two heavy quark pairs (*e.g.* DPS… or collisions with many hard scatterings?)

CDF in $p\bar{p}$:
First observation in 1998



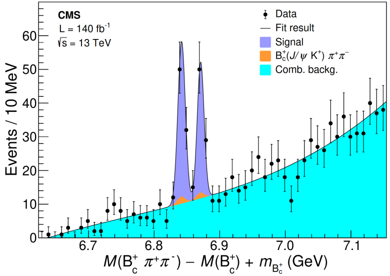
PRL 81 (1998) 2432

LHCb:
ratio of leptonic ($J/\psi\,\mu^+$) and hadronic ($J/\psi\,\pi^+$) channels $\simeq 20$



PRD 90 (2014) 032009

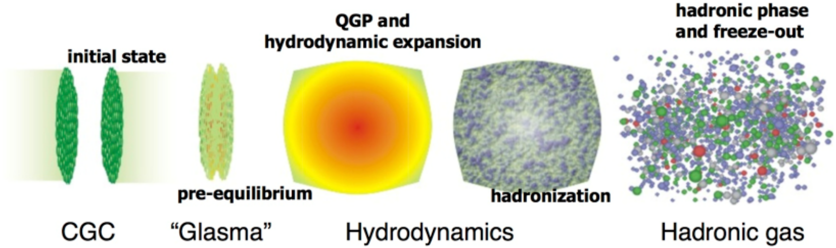
CMS:
observation of two excited states



PRL 122 (2019) 132001

Quark-gluon plasma

- QCD at very high temperature → deconfinement
  → quarks and gluons move freely in a quark-gluon plasma (QGP)
- Present during the first μs of the Universe (high T) and in neutron stars (high density)
- Reproduced in heavy ion collisions ($T \gg 10^{12}$ K)



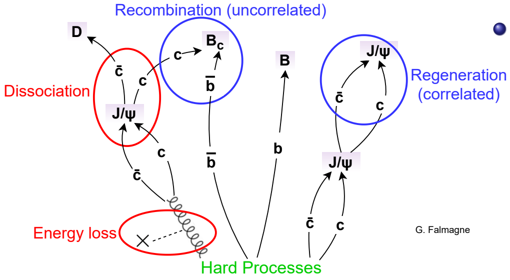
→ Can be probed comparing nucleus-nucleus and pp collisions at LHC:

$$R_{AA}^{X} = \frac{AA}{pp} = \frac{\frac{1}{N_{AA}^{MB} T_{AA}} \frac{\mathrm{d}N_{AA}^{X}}{\mathrm{d}p_T}}{\frac{\mathrm{d}\sigma_{pp}^{X}}{\mathrm{d}p_T}}$$

- Heavy quarks often produced on smaller time scales than QGP expansion
  → probe the whole QGP history

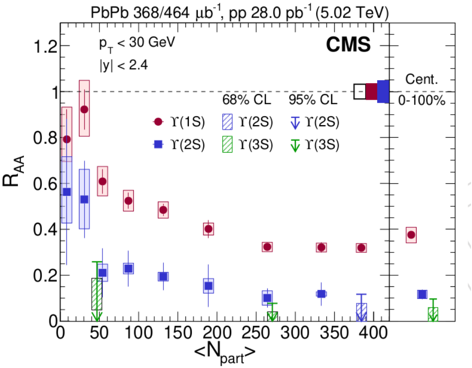
Quarkonia in the QGP: dissociation (1/3)

- 'Historical' effect: Debye screening of the heavy quark potential at finite temperature ($r_{q\bar{q}} > r_D$) + sequential suppression
- Laudau damping, dynamical screening ...



$\Upsilon(nS)$ with CMS

PLB 790 (2019) 270



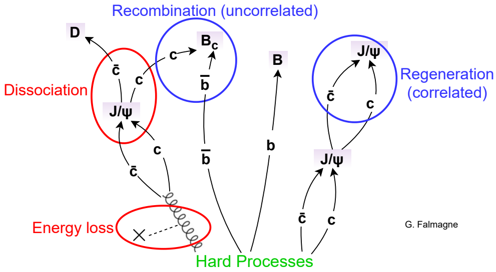
Quarkonia in the QGP: recombination (2/3)

- Dissociation, but ... J/ψ less suppressed at higher $\sqrt{s}$?

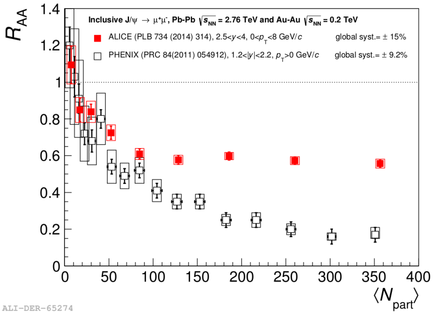
  $\longrightarrow$ Recombination of charm quarks from different hard processes:

  200 $c\bar{c}$ pairs in 0-5% central PbPb collisions at LHC!

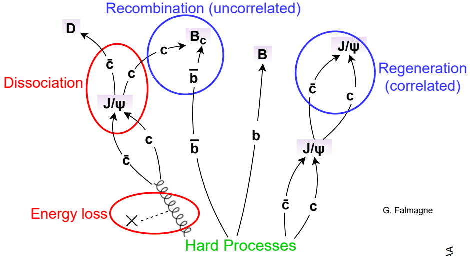
  $\longrightarrow$ Transport model, statistical hadronisation,comovers...



J/ψ ALICE vs PHENIX

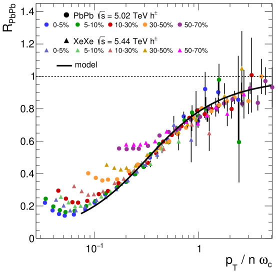


Quarkonia in the QGP: energy loss (3/3)

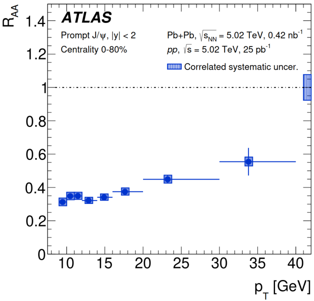


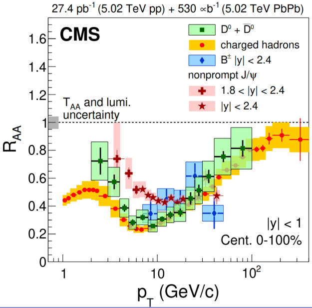
- Energy loss on the precursor parton ⟶ modification of spectra:
  - Collisional (low-p_T)
  - Mostly radiative (medium-induced emitted gluons) at high p_T, with universal behaviour
  - Expected mass and color charge dependence

PRL 119 (2017) 062302 + PoS (HP2018) 075



EPJC 78 (2018) 762

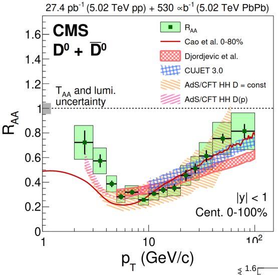




Recent history of heavy flavours in CMS heavy ions

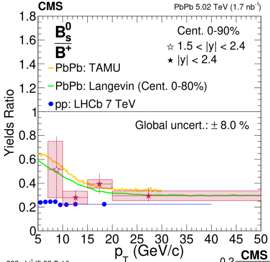
D^0: energy loss and dead-cone? Elliptic flow?

PLB 782 (2018) 474



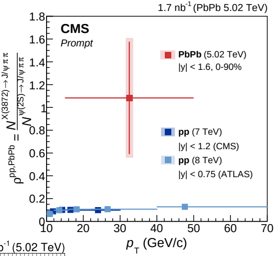
B^+ and B_s^0: Strangeness enhancement in b hadrons?

CMS-PAS-HIN-19-011



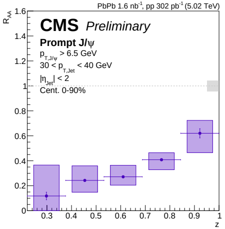
X(3872): compact tetraquark or $D^0 - \bar{D}^{0*}$ molecule?

arXiv:2102.13048

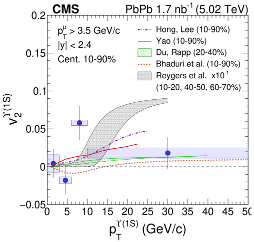


J/ψ: is it produced in parton showers?

arXiv:2106.13235



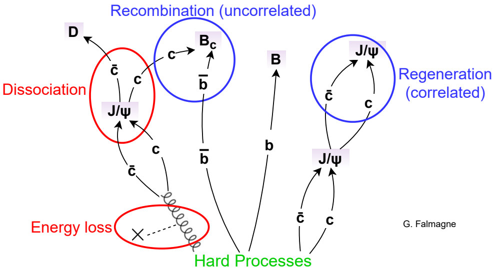
PLB 819 (2021) 136385



$v_2(\Upsilon)$: path-length dependence of energy loss?

Motivations to observe B_c in PbPb collisions

- Dissociation:
  binding energy between that of J/ψ and Υ



Motivations to observe B_c in PbPb collisions

- Dissociation:
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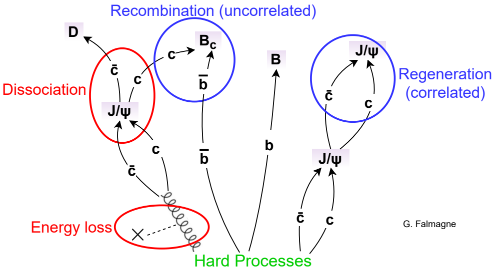
- Recombination of b with uncorrelated c quark?
  small $\sigma_{\mathrm{pp}}^{B_c}$ $\longrightarrow$ enhancement at $p_T \lesssim m_{B_c}$ could be dramatic !



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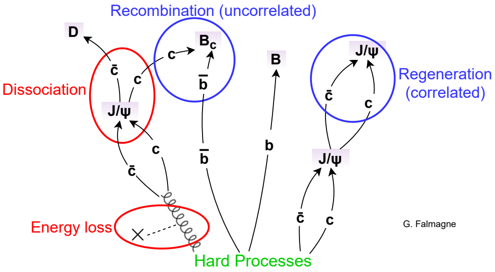
  could be dramatic !

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

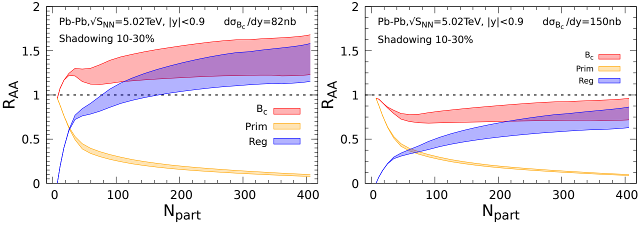
$\longrightarrow$ B_c = bridge between $c\bar{c}$ and $b\bar{b}$
and between open charm and open beauty



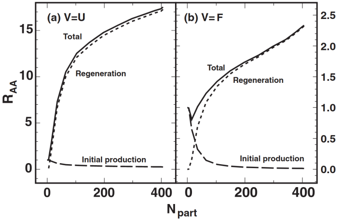
Motivations for B_c: phase-space-integrated predictions

- Many predict more regenerated than primordal B_c in PbPb!

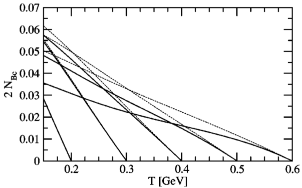
- TAMU transport model (B. Wu, Z. Tang and R. Rapp, in prep., based on PRC96(2017)054901 & NPA 859 (2011) 114)
- CAVEAT: inclusive (p_T-integrated) (whereas CMS looks at $p_T > 6$ GeV ⟶ expected drop of recombination)



- Liu, Greiner, Kostyuk (PRC **87** (2013), 014910) ⟶ $2 < R_{AA} < 18$

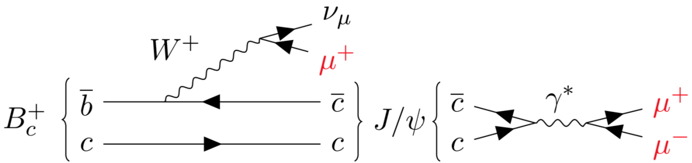


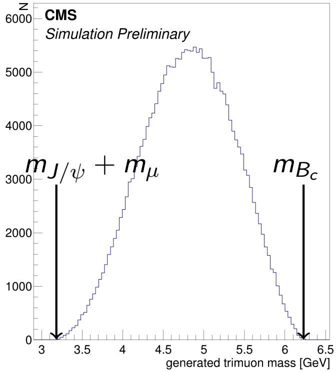
- Schroedter, Thews, Rafelski: $\sim \times 500$ enhancement in PRC **62** (2000), 024905



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 $B_c^+ \to J/\psi\,\pi^+$
  (hadronic channel manageable in pp 5.02 TeV, but S/B in PbPb is too low)
  - 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 ($\simeq$ 15% different in average, but wide spread)





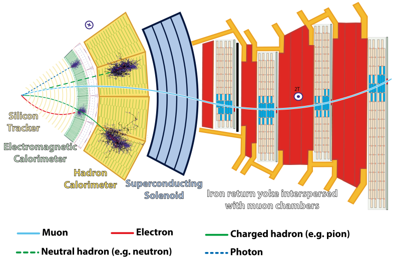
Analysis

CMS data, trigger, MC

- 2017 pp and 2018 PbPb data at $\sqrt{s_{NN}} = 5.02$ TeV ($\mathcal{L}_{\mathrm{PbPb}} = 1.61\ \mathrm{nb}^{-1}$, $\mathcal{L}_{\mathrm{pp}} = 302\ \mathrm{pb}^{-1}$) with dimuon trigger (with quality cuts)
- Simulations:
  - BCVEGPY specific generator for B_c MC (+PYTHIA8)
  - PYTHIA8 for (non)prompt J/ψ MC
  - EVTGEN1.3 for decays + GEANT4 for detector
  - Normalisation from previous measurements (pp only for B_c) p_T reweighting for J/ψ MC
- Each experiment has drawbacks to observe B_c:
  - ALICE: low luminosity and limited rapidity acceptance
  - LHCb: no central events
  - ATLAS and CMS: limited low-p_T acceptance (where B_c recombination is expected)

CMS single muon acceptance

- Use *global muons*: matching tracks from the inner tracker (momentum resolution) and from the muon chambers (muon identification)



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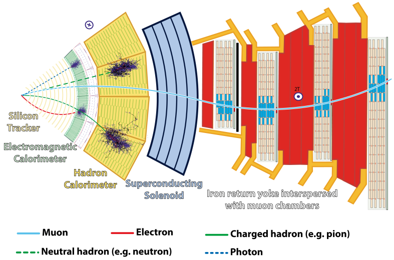
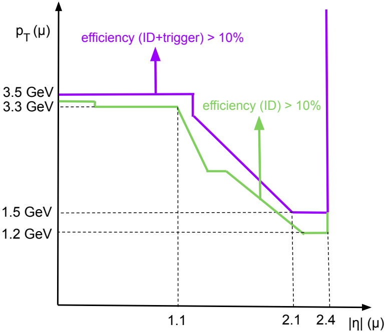


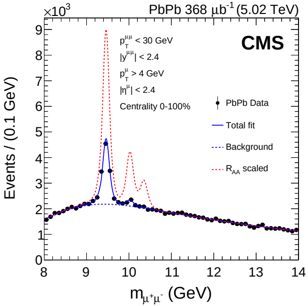


- Drawback: strong magnetic field (for momentum resolution) and thick detector layers ⟶ no low-p_T muons
- Keep muons that pass :
  - Standard identification criteria (ID)
  - Geometric acceptance cuts, defined such that total efficiency $> 10\%$, depending on trigger requirement

CMS advantages: dimuon studies

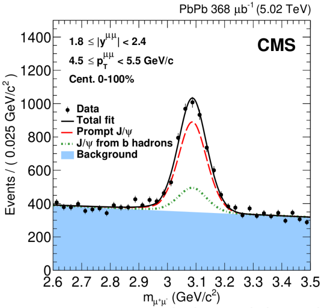
- B_c signal signature = 3 muons from a displaced vertex, with an opposite-sign pair in the J/ψ peak region
- CMS advantages:
  - excellent muon momentum and vertex resolutions
  - high luminosity

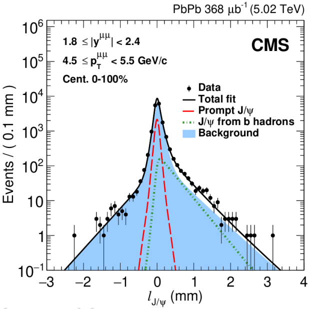
$\Upsilon(nS)$ PLB 790, 270



J/ψ mass

EPJC 78 (2018) 509

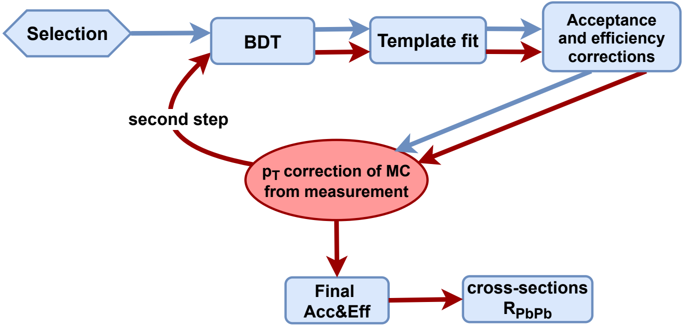




J/ψ displacement

Analysis strategy

- Selection + BDT



Analysis strategy

- Selection + BDT
- Trimuon mass templates
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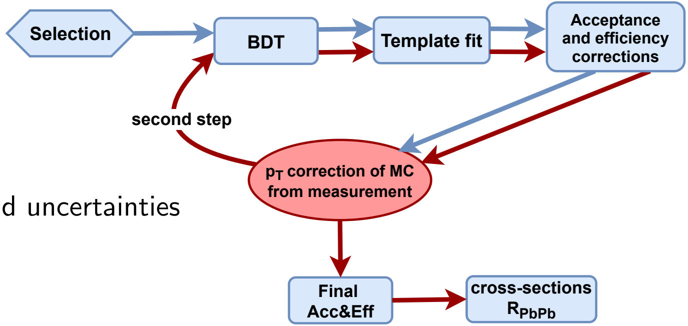
- Template fit of trimuon mass.
  Nuisance parameters for background uncertainties



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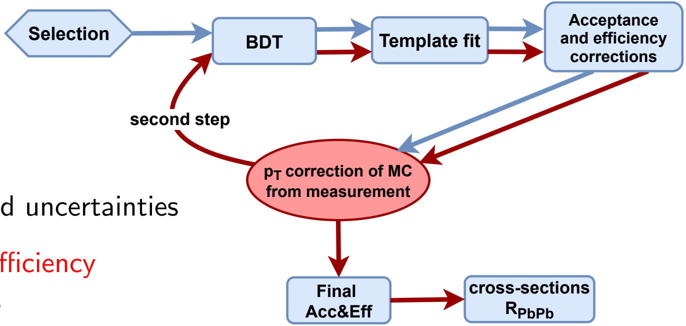
  ⟶ final acceptance and efficiency and related uncertainty



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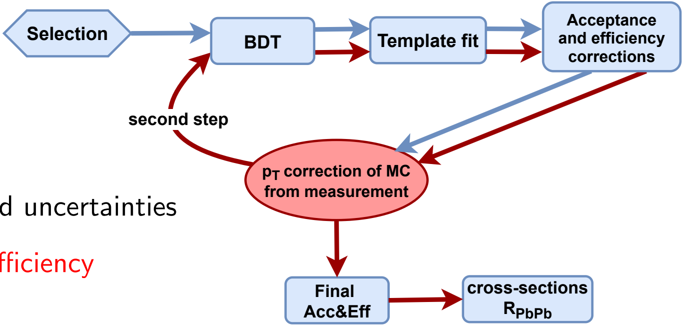
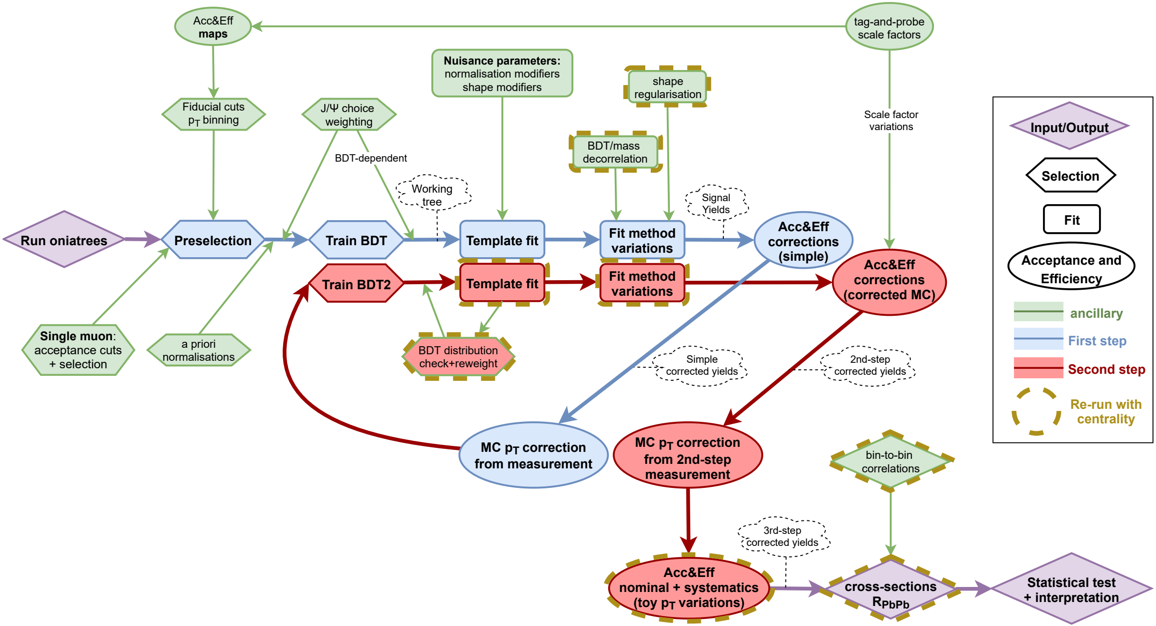
- Result: $R_{PbPb}(B_c)$ in two p_T or centrality bins, with some rapidity cuts



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

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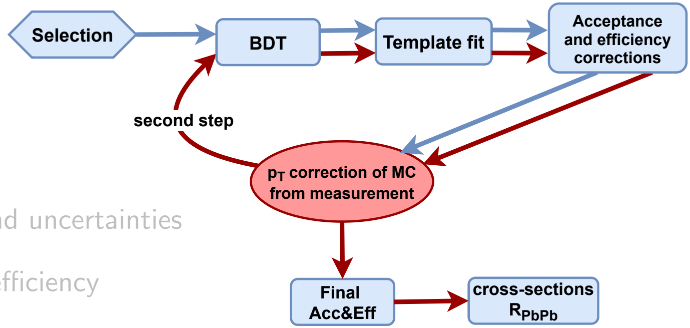
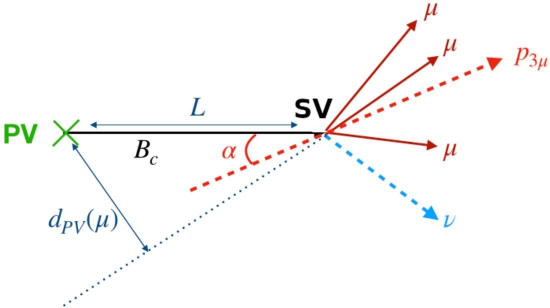


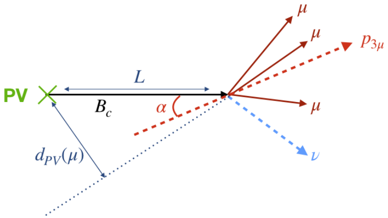
Selection

- Three muons from a displaced vertex, with standard identification criteria
- 2 out of 3 muons fire the trigger ⟶ looser acceptance for third muon
- Cut selection on these variables:
  - Trimuon and dimuon vertex probability
  - Lifetime significance $L/\sigma(L)$
  - Muon displacement from the PV: $d_{z,PV}(\mu)$
  - Angle α between trimuon momentum and flight direction PV-SV
  - Sum of the pseudo-angles ΔR between the muon pairs
  - Trimuon mass corrected for $p_\perp(\nu)$

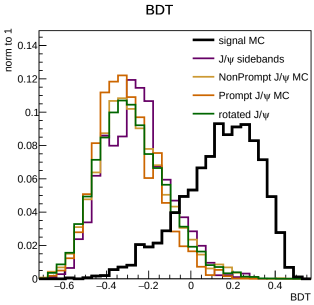


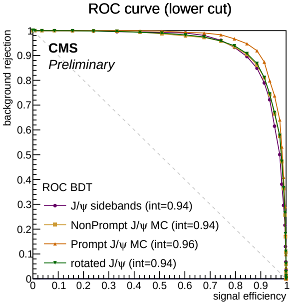
BDT

- Will fit in 3 BDT ranges
- Train BDT (TMVA), separately in 2 p_T bins (evaluation and training on two independent halves)



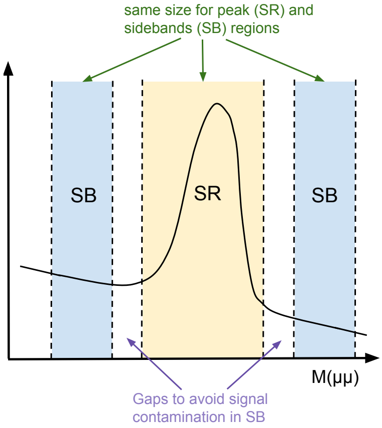
- Use 5 previous violet variables, plus:
  - μ_W significance of displacement from PV
  - Imbalance between $p_T(\mu_W)$ and $p_T(J/\psi)$
  - Ratio between $\Delta R(J/\psi)$ and ΔR of other dimuons





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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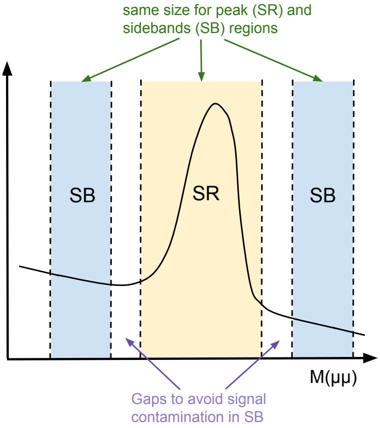
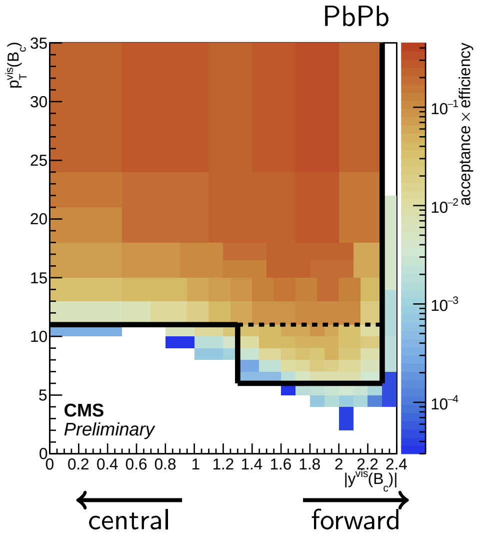


→ Keep both pairs as trimuon candidates, with weights of sum 1, corresponding to probability of being a J/ψ

- Weights extracted from unambiguous trimuons in selected data

Analysis bins (from acceptance and efficiency)

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



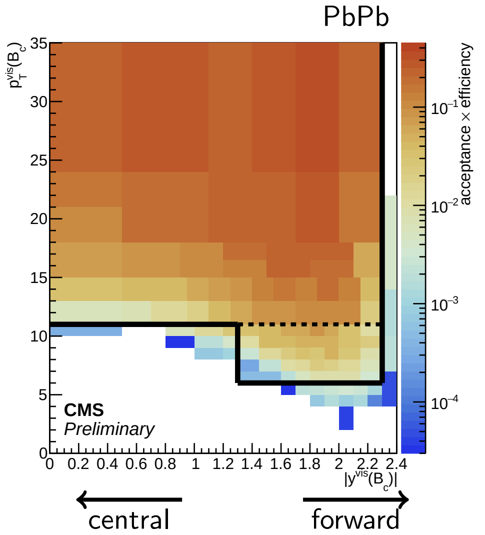
Analysis bins (from acceptance and efficiency)

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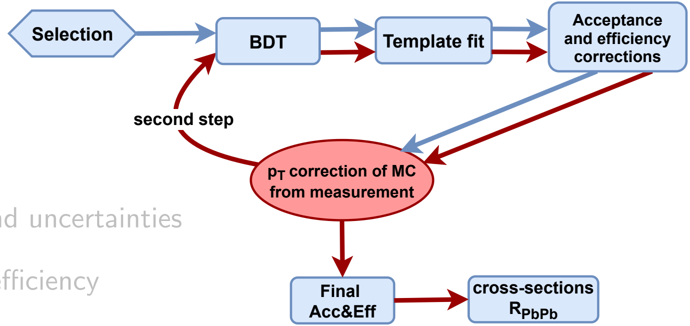

Categorisation of backgrounds

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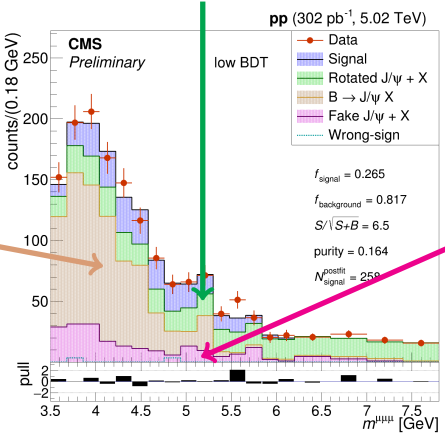
  NO → Data-driven rotated J/ψ sample
  (rotate the momentum and flight distance of all J/ψ's in data)
  YES ↓

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

Background shapes

- $J/\psi - \mu$ from $\neq$ vertices ⟶ use rotated J/ψ sample

- J/ψ and (mostly fake) muon from same *B decay*: from MC



- Fake J/ψ ⟶ dimuon mass sidebands

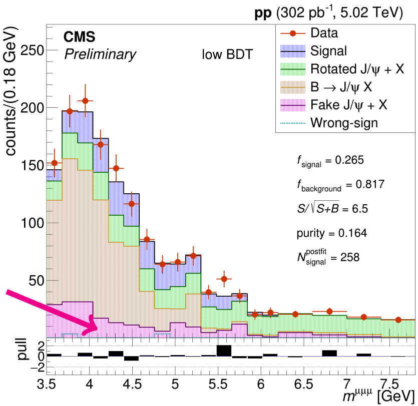
pp p_T-integrated fit (background-enriched BDT bin)

Fake J/ψ

- Fake J/ψ
  → use both **dimuon mass sidebands**

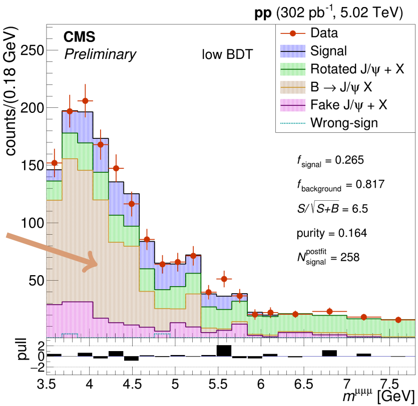
- **Data-derived normalisation**

- Slight differences between lower ($m_{\mu\mu} < m_{J/\psi}$) and upper sideband ($m_{\mu\mu} > m_{J/\psi}$)
  → nuisance parameter varies their relative contribution



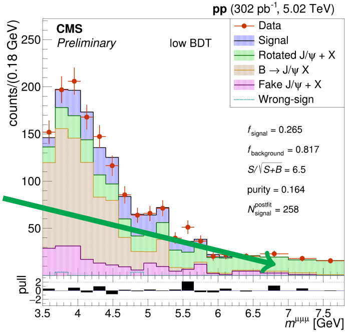
B decays

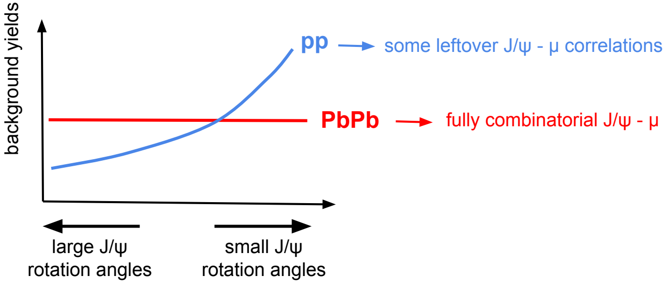
- J/ψ and muon from same B decay: from **non-prompt** J/ψ **MC**
- Mostly from misidentified hadron
- Free normalisation in fit (for misID rate)
- Cutoff at 5.3 GeV (maximal B mass)
- Very small (relative to other backgrounds) in PbPb



$J/\psi - \mu$ from different decay vertices

- $J/\psi - \mu$ from $\neq$ vertices ⟶ use **rotated** J/ψ sample
- Rotate (around primary vertex) the flight direction and momentum of data J/ψ (average over multiple angles)
- Data-derived normalisation in PbPb (constrained by high mass in pp)





- Leftover $J/\psi - \mu$ correlations (e.g. from J/ψ and muon from the B and $\bar{B}$ respectively) in pp ⟶ vary rotation angles

Analysis strategy

- Selection + BDT
- Trimuon mass templates
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- Template fit of trimuon mass.
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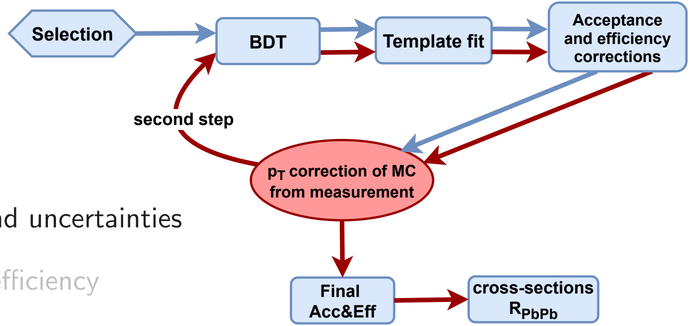


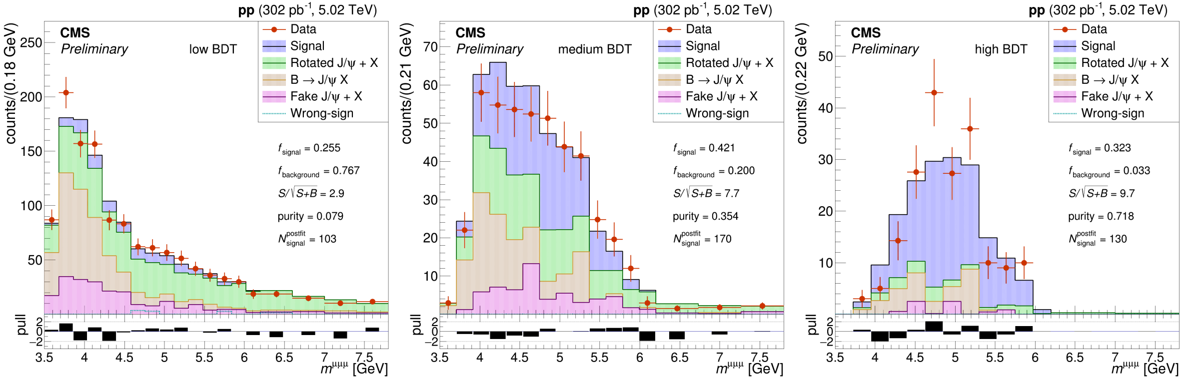
Template fit principle

- Likelihood fit over 3 BDT bins + 2 p_T or centrality bins
- Low-BDT regions stabilise the backgrounds, high-BDT determine signal yields
- Nuisance parameters to account for background uncertainties
  $\longrightarrow$ reflected on fit uncertainty:
  - Fake J/ψ *shape*: lower or upper sideband
  - Rotated J/ψ: free *normalisation* (in pp) + *shape* variations (*e.g.* angles)
  - B decays: free *normalisation* + *shape* variation (include part of MC in pp)
  - Vary the templates within their statistical uncertainties (one parameter per mass bin)

Template fit (pp low-p_T)

- Fit uncertainty 9%

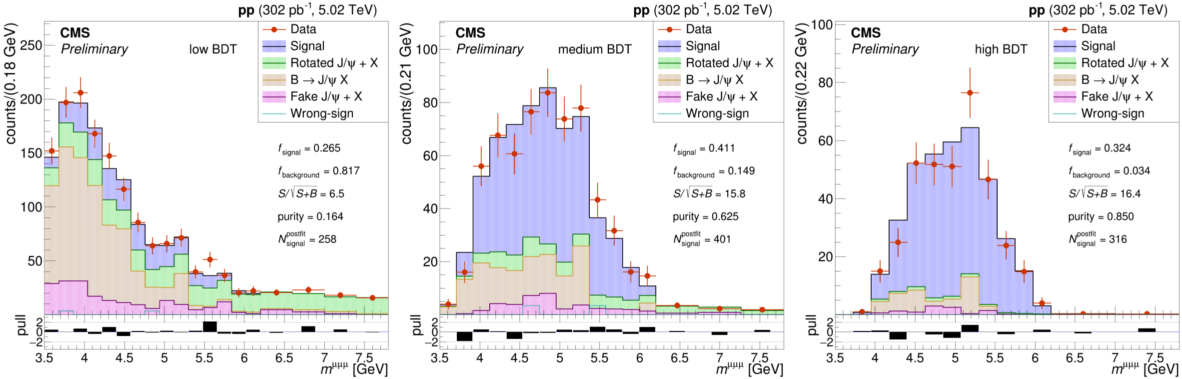
pp, $6 < p_T < 11$ GeV



Template fit (pp high-p_T)

- Fit uncertainty 5%

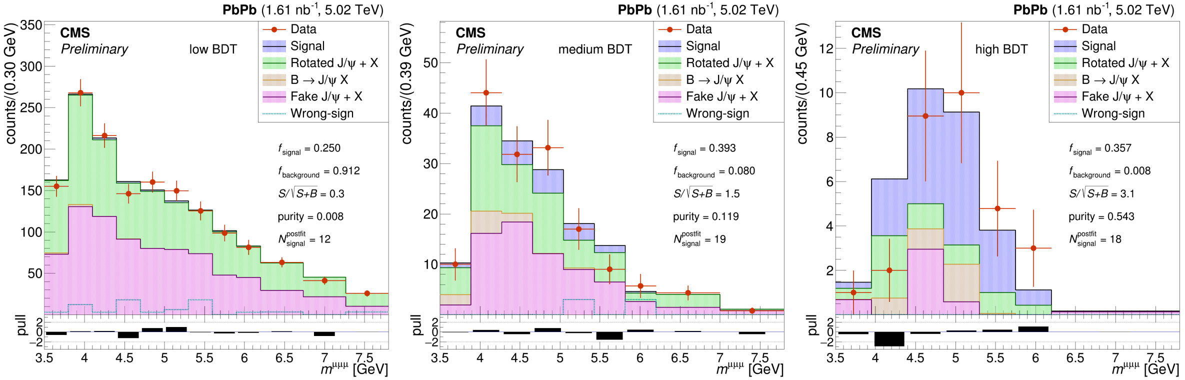
pp, $11 < p_T < 35$ GeV



Template fit (PbPb low-p_T)

- Fit uncertainty 31%

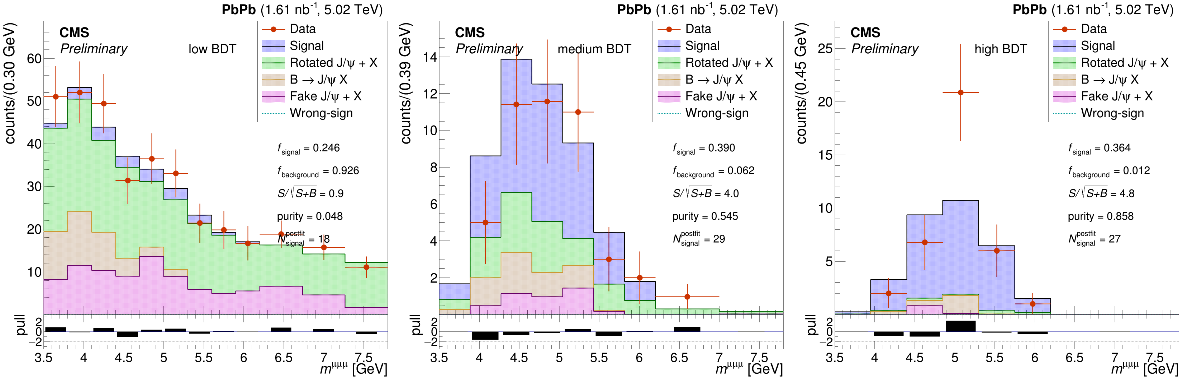
PbPb, $11 < p_T < 35$ GeV



Template fit (PbPb high-p_T)

- Fit uncertainty 17%

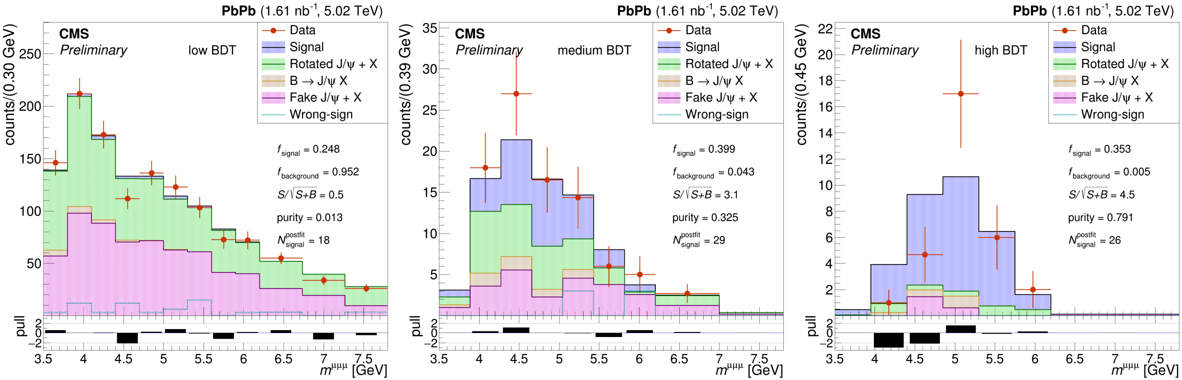
PbPb, $11 < p_T < 35$ GeV



Template fit (PbPb, central events)

- Fit uncertainty 20%

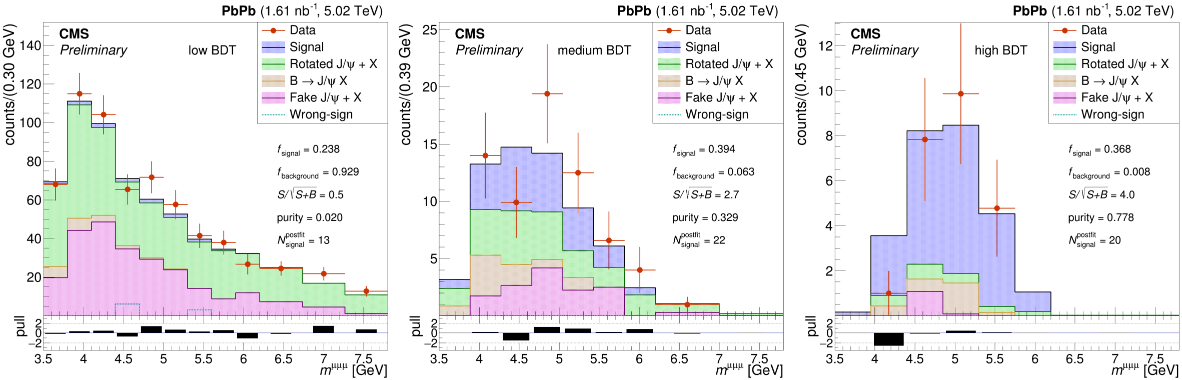
centrality 0 − 20% (p_T-integrated)



Template fit (PbPb, peripheral events)

- Fit uncertainty 23%

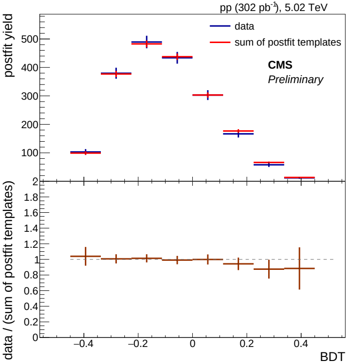
centrality 20 − 90% (p_T-integrated)



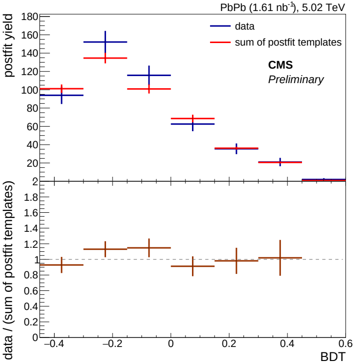
Check of BDT distributions

- 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, apply weights to all templates before a final re-fit. Comparison after final fit:

pp
1st p_T bin



PbPb
2nd p_T bin

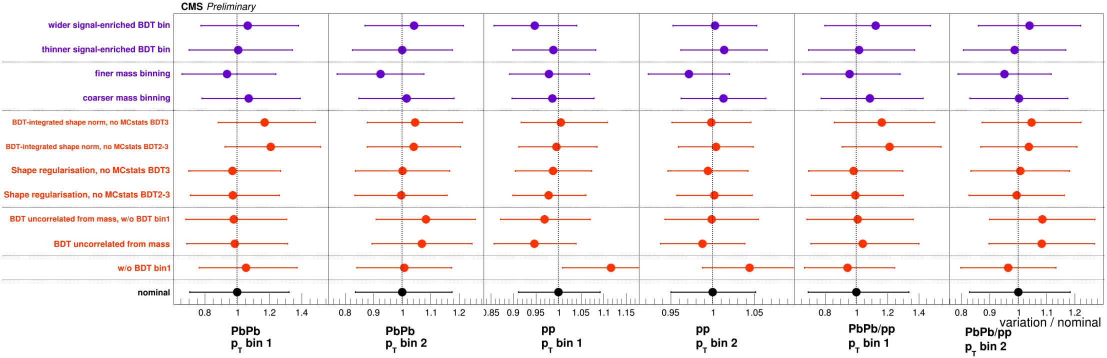


Variations of fit method

Stability of fit method? ⟶ 11 variations are considered:

- Ignore BDT bin 1 in the fit (i.e. less constrained backgrounds)
- Fit with an alternate BDT variable, decorrelated from mass (to leave discriminant power to the mass, see backup, 2 cases)
- 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 (2 cases)
- 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 (2 cases)
- Change mass binning *or* BDT binning (2 cases each)

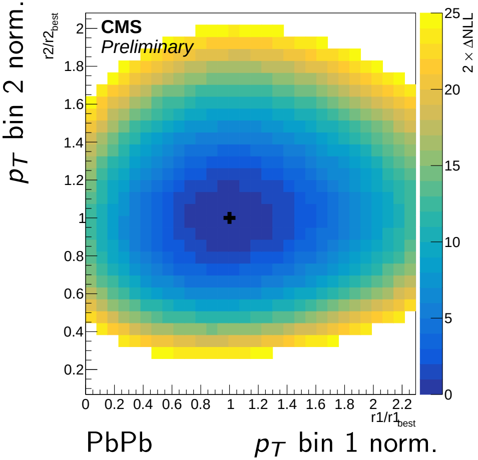
Fit method systematic uncertainty



- Systematic uncertainty = RMS of the 3 orange categories of methods
- Violet: only checks (consistent with nominal)

Significance of observation in PbPb

- Coloured blob is $< 5\sigma$ 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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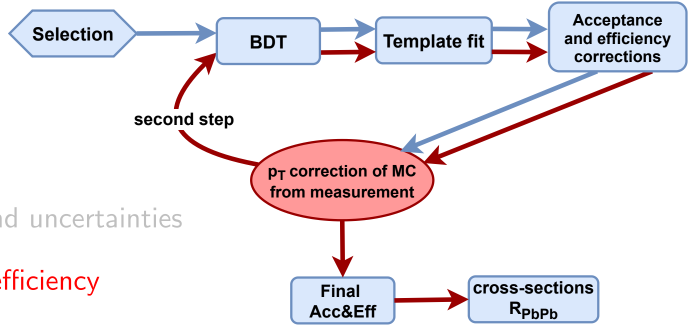
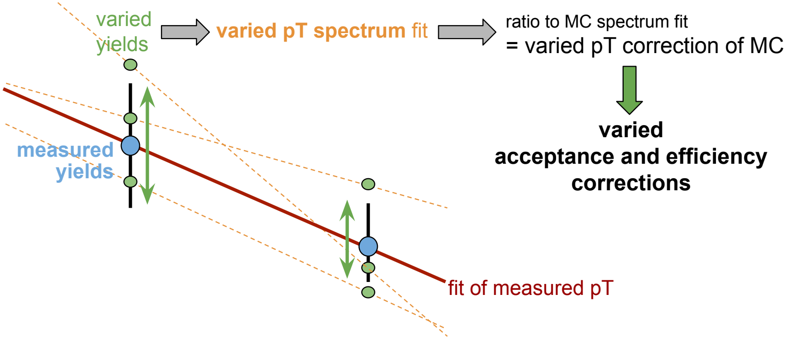


Acceptance and efficiency: iterative procedure

- Wide bins ⟶ $\alpha \times \varepsilon$ is sensitive to the assumed p_T spectrum shape
- Need to correct *with our measurement* the p_T spectrum of MC, before recalculating $\alpha \times \varepsilon$
- Re-run the whole analysis with corrected MC
  ⟶ Correct MC again
  ⟶ final acceptance and efficiency
- The procedure converges rapidly (very small differences between second and third estimations)

Acceptance and efficiency: Uncertainty



- For p_T-integrated bins: uncertainty = RMS of varied $\alpha \times \varepsilon$ ($\longrightarrow$ dominant 21-25%)
- For p_T bins: correlations between $\alpha \times \varepsilon$ and other uncertainties
  $\longrightarrow$ Full uncertainty = RMS of varied observed yield $\times$ varied $\alpha \times \varepsilon$ correction
  $\longrightarrow$ 26% at low-p_T, very small at high p_T thanks to correlations

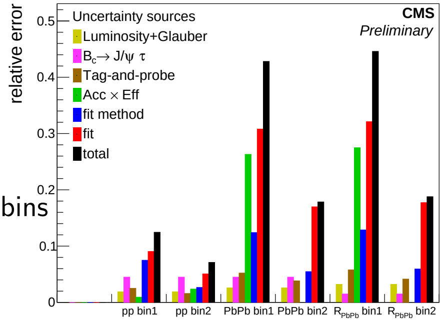
Other (small) uncertainties

- Tag-and-probe (scale factors on efficiency): 2-6%
- Contamination from other B_c decays:
  mostly $B_c \to J/\psi\,(\tau \to \mu\,X)\,\nu_\tau$ and $B_c \to (c\bar{c} \to J/\psi\,X)\,\mu\,\nu_\mu$
  ⟶ estimated $\lesssim$ 4.5% due to lower efficiency and branching fractions
  + partially cancels in R_{PbPb} (1%)
- Luminosity + centrality determination: 1.9-3.6%

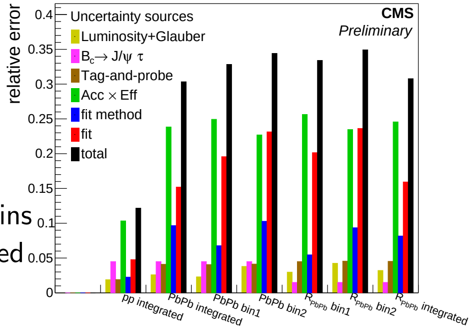
Summary of uncertainties

- Fit uncertainty (statistical+systematic) (dominates in p_T bins)
- Fit method variation
- Acceptance and efficiency (dominates p_T-integrated bins)
- Tag-and-probe
- Contamination from other B_c decays + luminosity and centrality

p_T bins



centrality bins + integrated



Results

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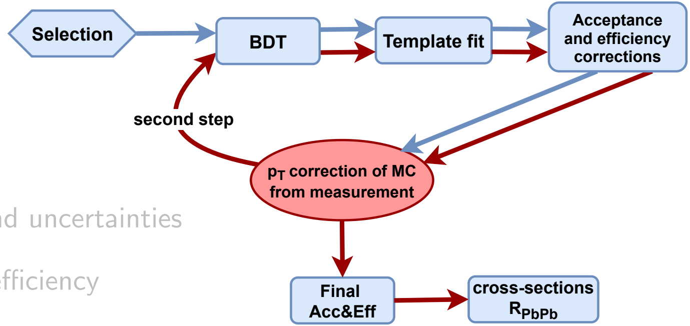
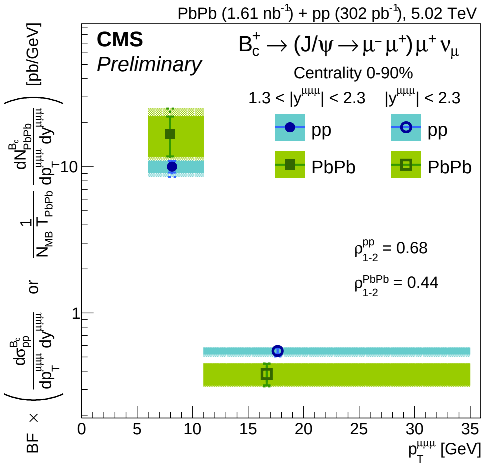
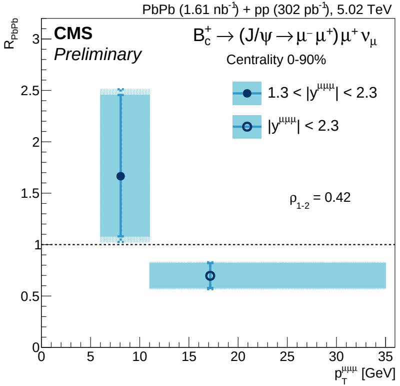


Cross sections



- Scale corrected yields by luminosity (pp) or pp-equivalent luminosity (PbPb)
- Correlation between bins fully calculated
- pp cross section integrated on p_T used for centrality bins

First $R_{PbPb}(B_c)$!



Uncertainties: bin-to-bin-uncorrelated VS total

- Difference between two p_T bins: 1.6σ significance

⟶ Consistent with softening of p_T spectrum in PbPb collisions

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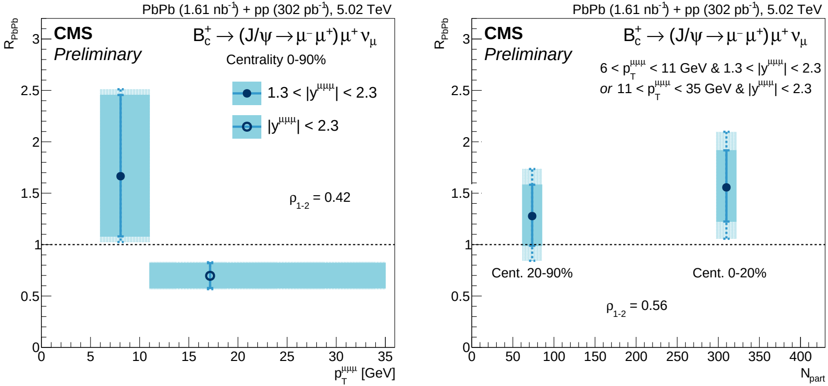
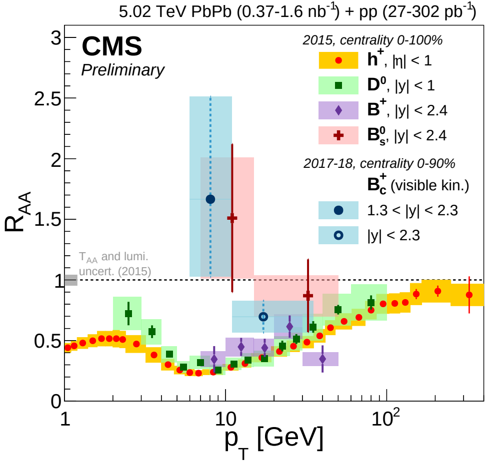


Uncertainties: bin-to-bin-uncorrelated VS total

- Difference between two p_T bins: 1.6σ significance
  $\longrightarrow$ Consistent with softening of p_T spectrum in PbPb collisions
- If same central values and $2\times$ smaller uncertainties (Run 4 + detector upgrades?)
  $\longrightarrow$ new evidence of recombination, because primordial B_c is expected to be dissociated!

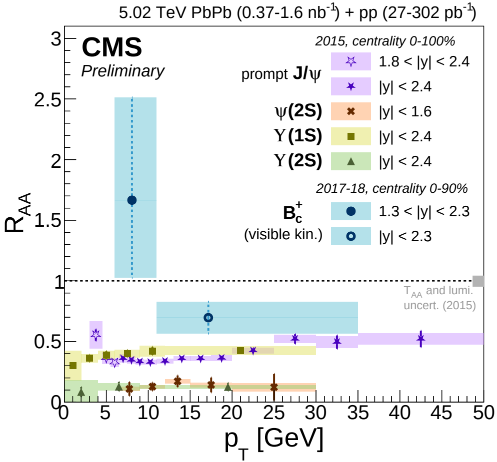
Comparison with open heavy flavour at CMS

- B_c and B_s modifications are similar
- Less suppression than light hadrons, B and D
- All species seem to converge at high-p_T
  ⟶ Universal radiative energy loss?
- Species diverge at low/medium-p_T
  ⟶ different dissociation or recombination effects?
  Flavour dependence of energy loss?
  ⟶ Need more data
  (and model-discriminant observables)!



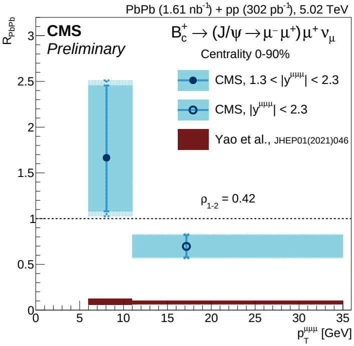
Comparison with hidden heavy flavour at CMS

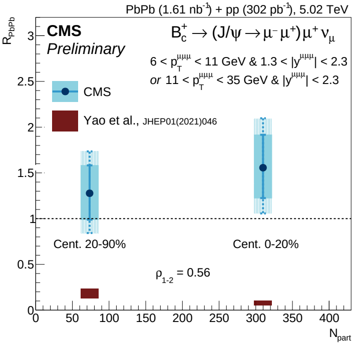
- B_c less suppressed than quarkonia
  → different mechanisms at play than in hidden heavy flavour, despite similar quark content?
- Binding energy between J/ψ and Υ
  → would expect a hierarchy if dissociation was the sole effect...
- If central values are confirmed in Run 4: much more recombination than in J/ψ, worth trying in ALICE at low p_T (even for an upper limit)!



Comparison with one theory prediction

- Received one theory contribution yet, from Yao et al JHEP01 (2021) 46:
  - Transport model including correlated and uncorrelated recombination.
  - B_c (not trimuon) kinematics are used + no feed-down included

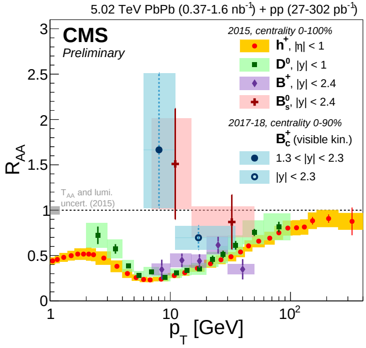


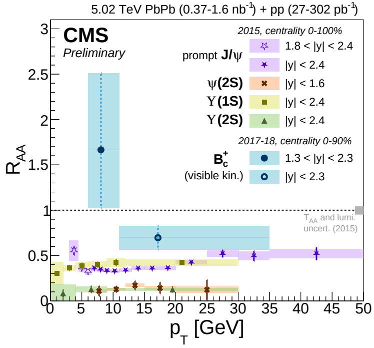


- Lower values than measurement. But no recombination of excited B_c states is included...
  → importance of recombination in B_c production (including cross-talk with excited states) ?
- Predicts 2× higher R_{PbPb} in peripheral than central
  → not seen in measurement
- Many more regenerated than primordial B_c needed!

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!



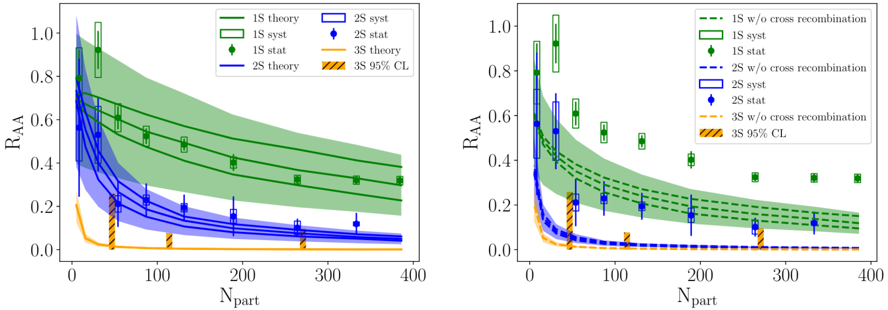


→ What will this look like in Run 4, with contributions from other experiments?

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:
  $|\eta| < 2.4 \,\&$
  $((|\eta| < 1.2 \,\&\, p_T \geqslant 3.5)$
  $||(1.2 \leqslant |\eta| \,\&\, |\eta| < 2.1 \,\&\, p_T \geqslant 5.47 - 1.89 * |\eta|)$
  $||(2.1 \leqslant |\eta| \,\&\, p_T \geqslant 1.5))$

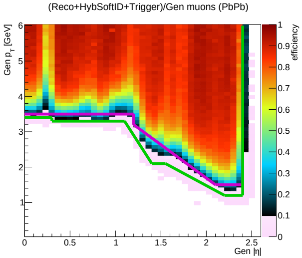
Single-muon acceptance + selection

- Two muons must pass the J/ψ trigger, the third one only Hybrid-soft

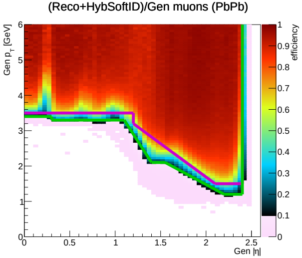
- Hybrid-soft is:
  - Passes *global* and *tracker* muon ID
  - $d_{xy} < 0.3$ cm and $d_z < 20$ cm
  - tracker layers with measurement > 5
  - pixel layers with measurement > 0

PbPb single-muon efficiencies:

Hybrid-soft + trigger



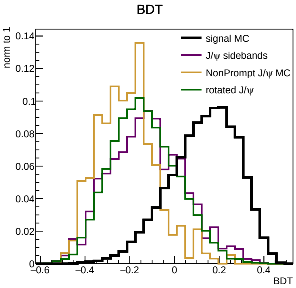
Hybrid-soft selection

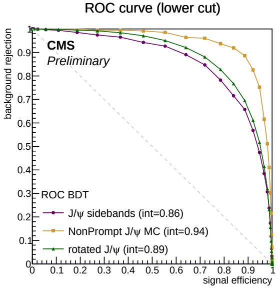


- Single-muon acceptance cuts from **efficiency** $\gtrsim$**10%**
- Looser acceptance cuts for the non-triggering muon

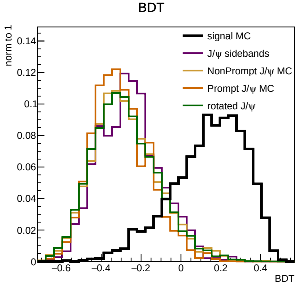
BDT variable

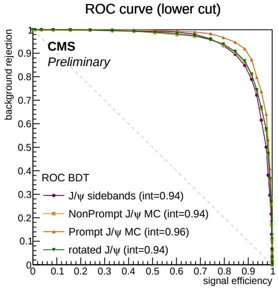
pp





PbPb





Uncorrelate BDT from trimuon mass

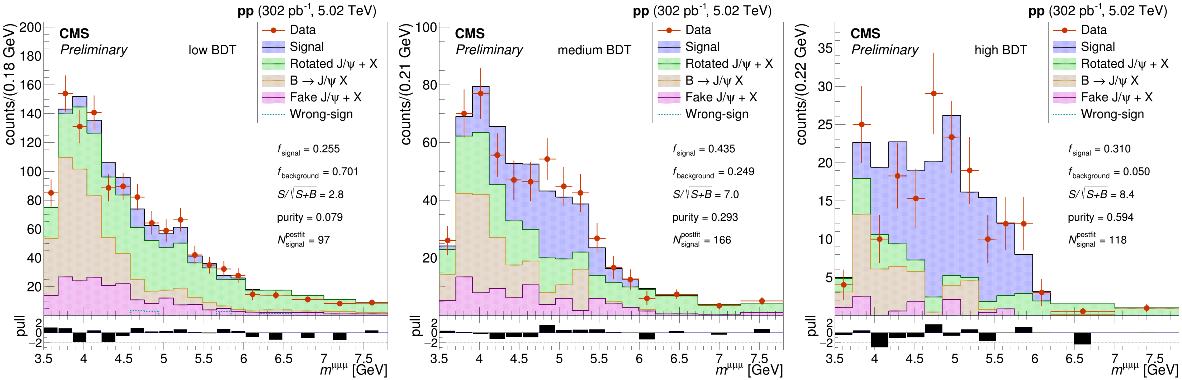
- The BDT, when optimising, realises that most signal is in [4.5,5.5] GeV...
  → steals discriminative power from the template fit procedure
- Decorrelate BDT value from mass (in each p_T or centrality bin), and use alternative fit in the systematics
- Subtract the mean BDT mass (of total background)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

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

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

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

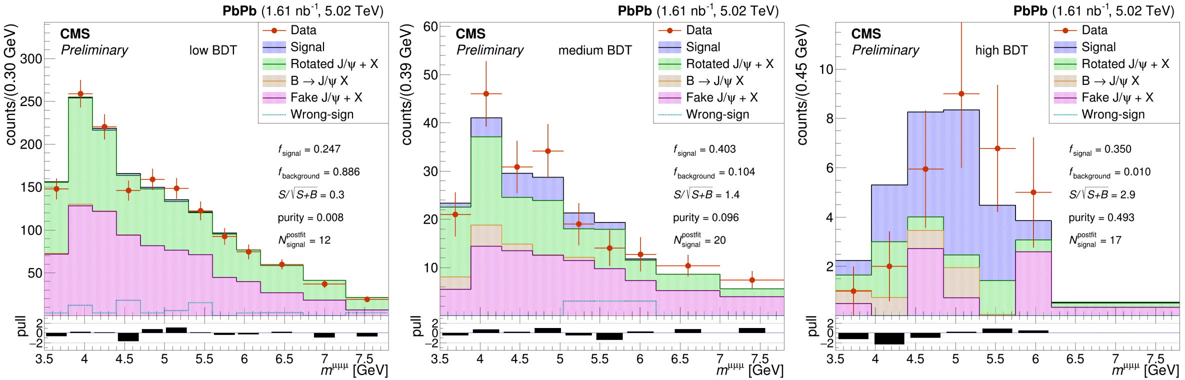
pp, $6 < p_T < 11$ GeV



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

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

PbPb, $6 < p_T < 11$ GeV



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