

# Studies of heavy flavor dynamics using $B^+$ , $B_s$ , and $B_c^+$ mesons with CMS

Based on the publications

$B_s / B^+$ , [PLB 829 \(2022\) 137062](#)

$B_c^+$ , [arXiv:2201.02659](#) (accepted by PRL)



**Florian Damas** for the CMS collaboration  
Laboratoire Leprince-Ringuet (École Polytechnique, CNRS-IN2P3)

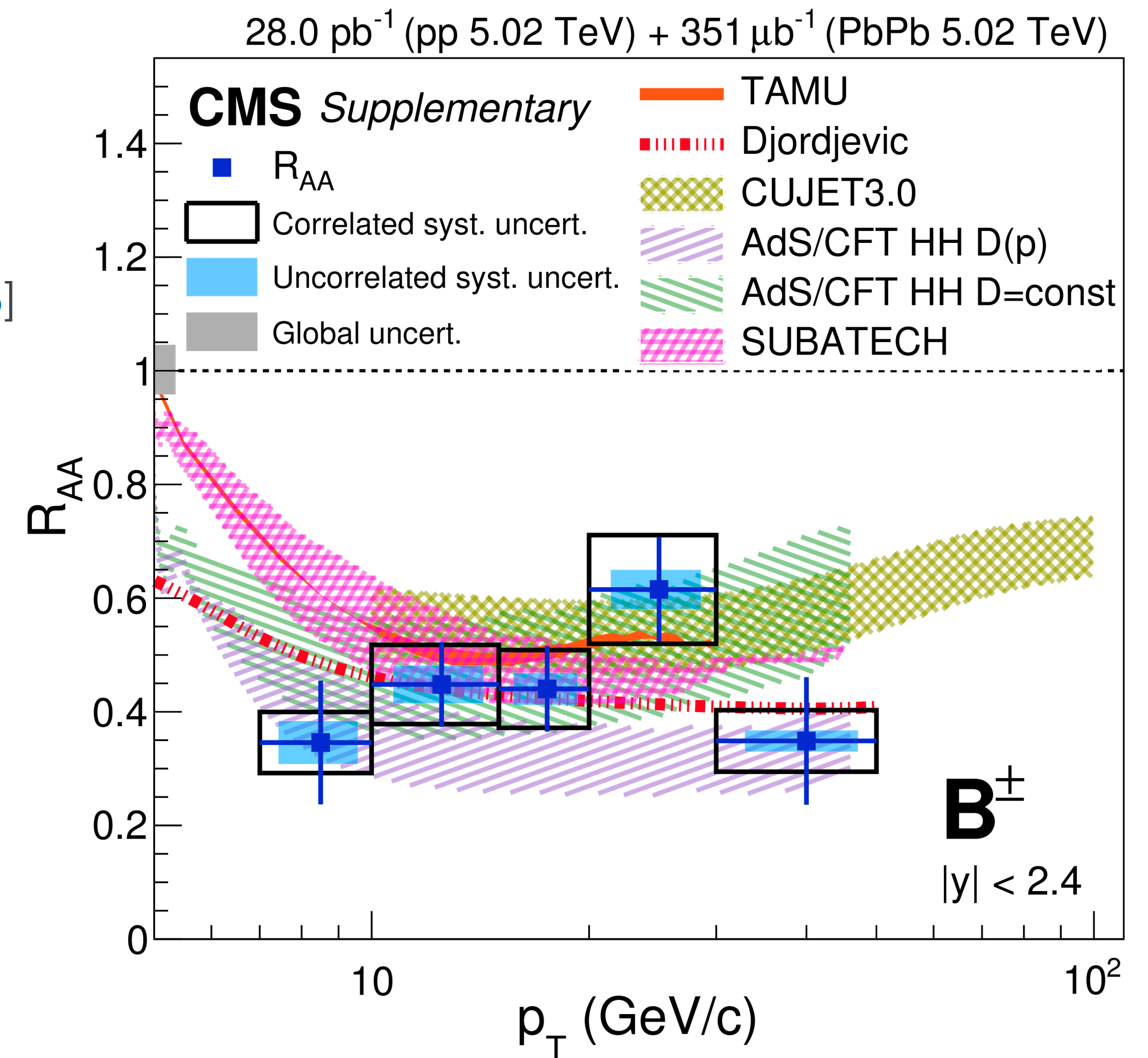
Strangeness in Quark Matter conference  
14 June 2022, Busan (Republic of Korea)

First measurement of  $B^\pm$  in PbPb collisions

Heavy quarks are well-known probes of the QGP.

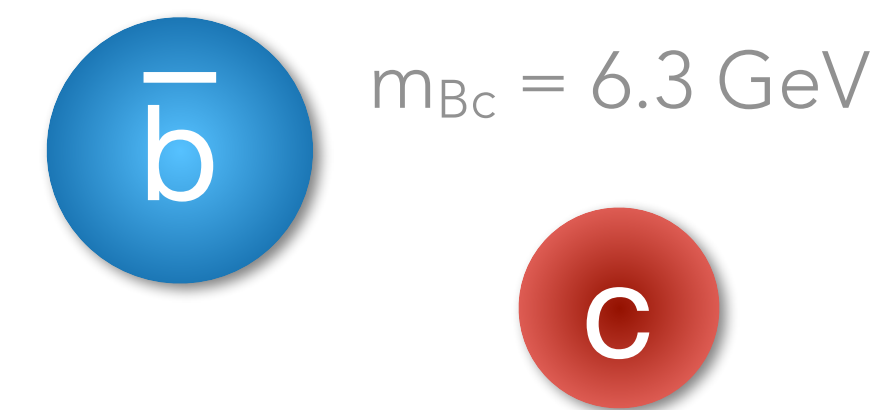
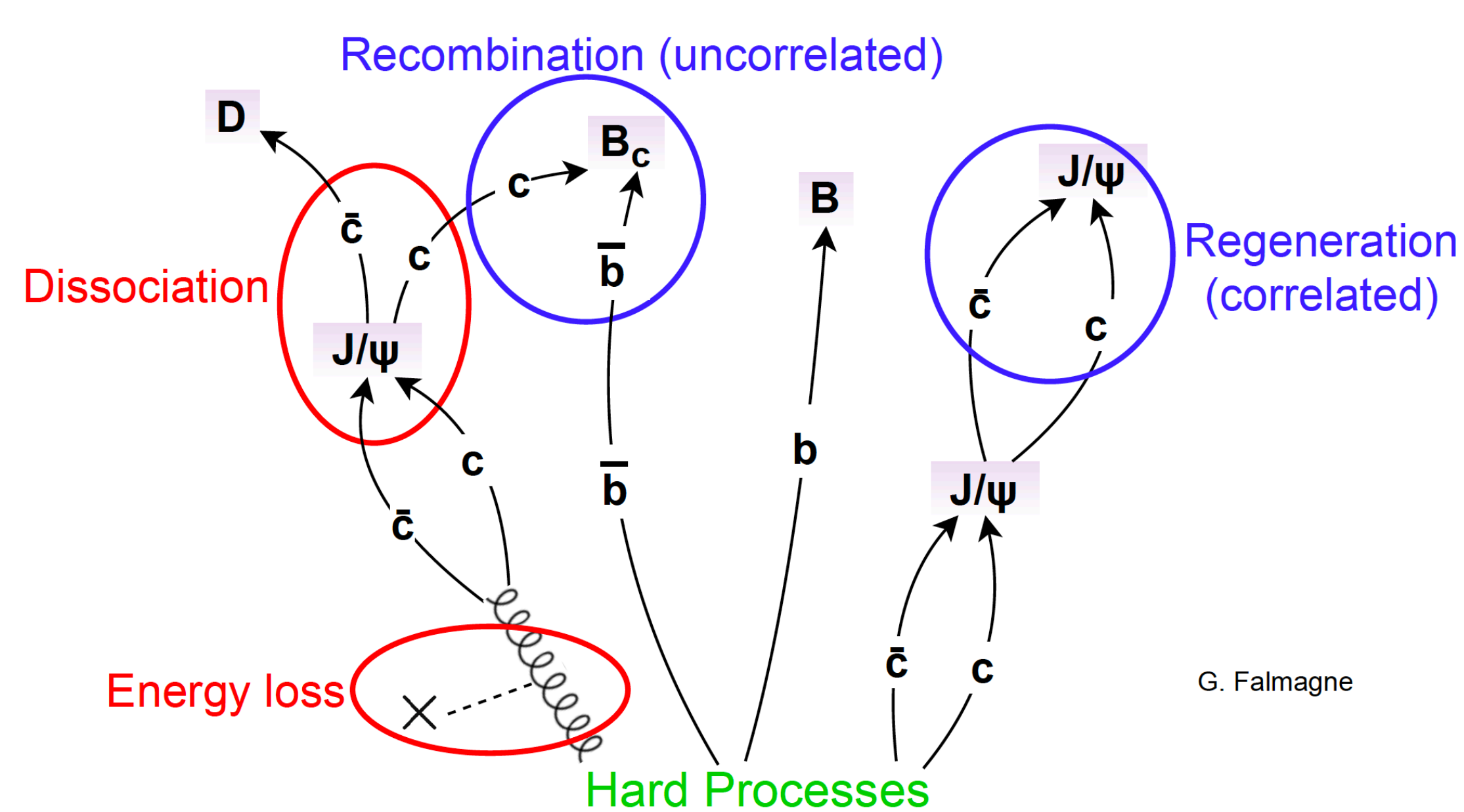
## New insights with beauty:

- ▶ pQCD calculations more accurate than for charm
  - ☛ extraction of **transport properties** [NPA 979 (2018) 21-86]
  
- ▶ collisional and radiative energy loss
  - ☛ **test mass and flavor dependences**
  
- ▶ constraints on **hadronization mechanism(s)**
  - ☛ **fully-reconstructed b-hadron decays**
  - ☛ strangeness enhancement for open heavy-flavor hadrons via  **$B_s/B^+$  yield ratio**



PRL 119 (2017) 152301

Model references: [PLB 735 \(2014\) 445](#), [PRC 94 \(2016\) 044908](#),  
[JHEP 02 \(2016\) 169](#), [PRD 91 \(2015\) 085019](#), [PRC 93 \(2016\) 044909](#)



## Hybrid quarkonium state

- ▶ mass and binding energy between  $J/\psi$  and  $\Upsilon(1S)$
- ▶ sensitive to **medium-induced dissociation**

- ▶ small production cross section in pp collisions
- ▶ low- $p_T$  enhancement via the **recombination** of beauty and charm quarks within the QGP

- ▶ probing the mass, flavor, and color charge dependence of **energy loss mechanisms** (high  $p_T$  regime)

Compilation of CMS

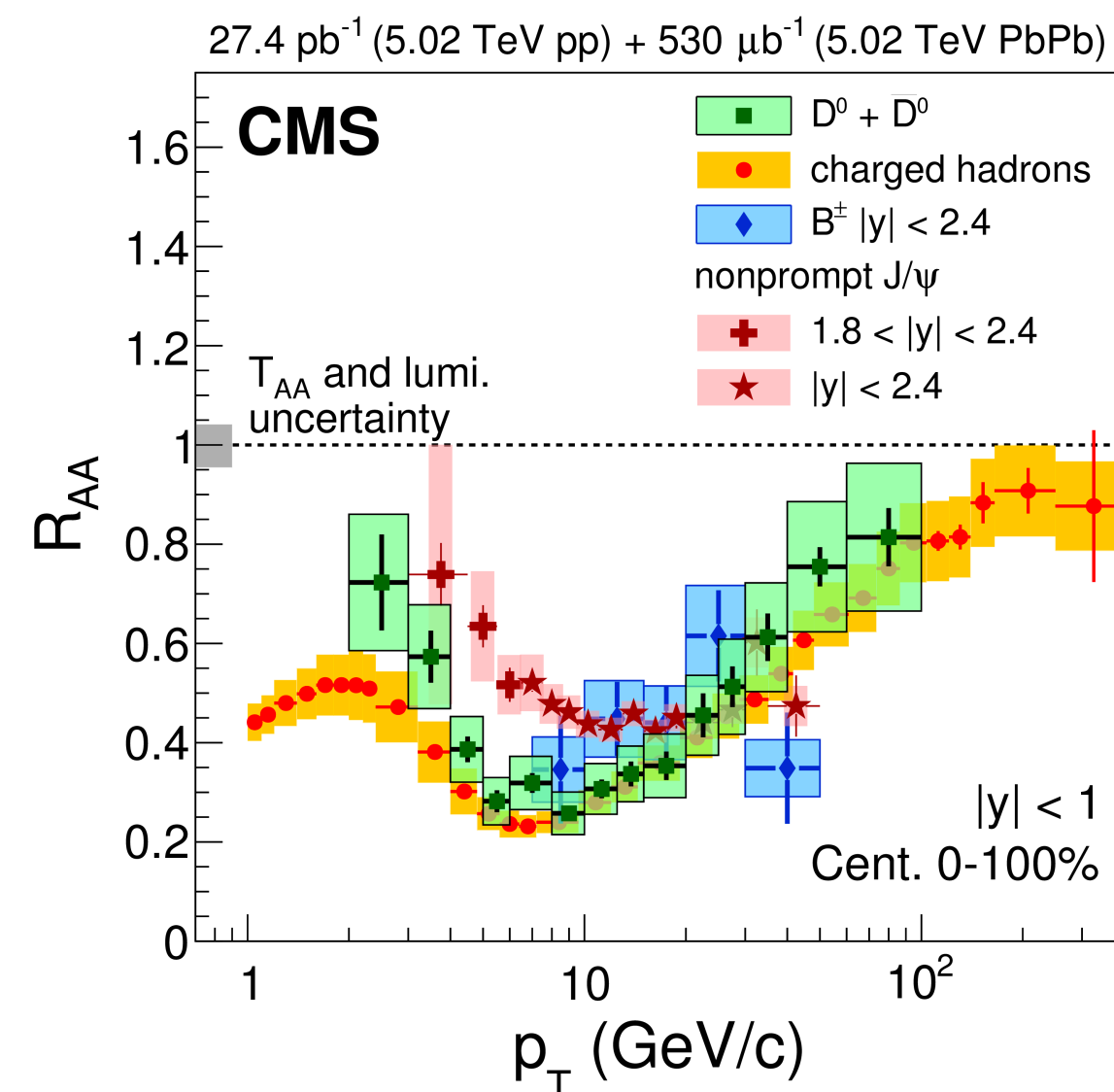
$R_{AA}$  measurements

$D^0$ , PLB 782 (2018) 474

$h^\pm$ , JHEP 04 (2017) 039

$B^\pm$ , PRL 119 (2017) 152301

$b \rightarrow J/\psi$ , EPJC 78 (2018) 509



Ideal experiment to reconstruct **exclusive b-hadron decays involving  $J/\psi \rightarrow \mu^+\mu^-$  final states**

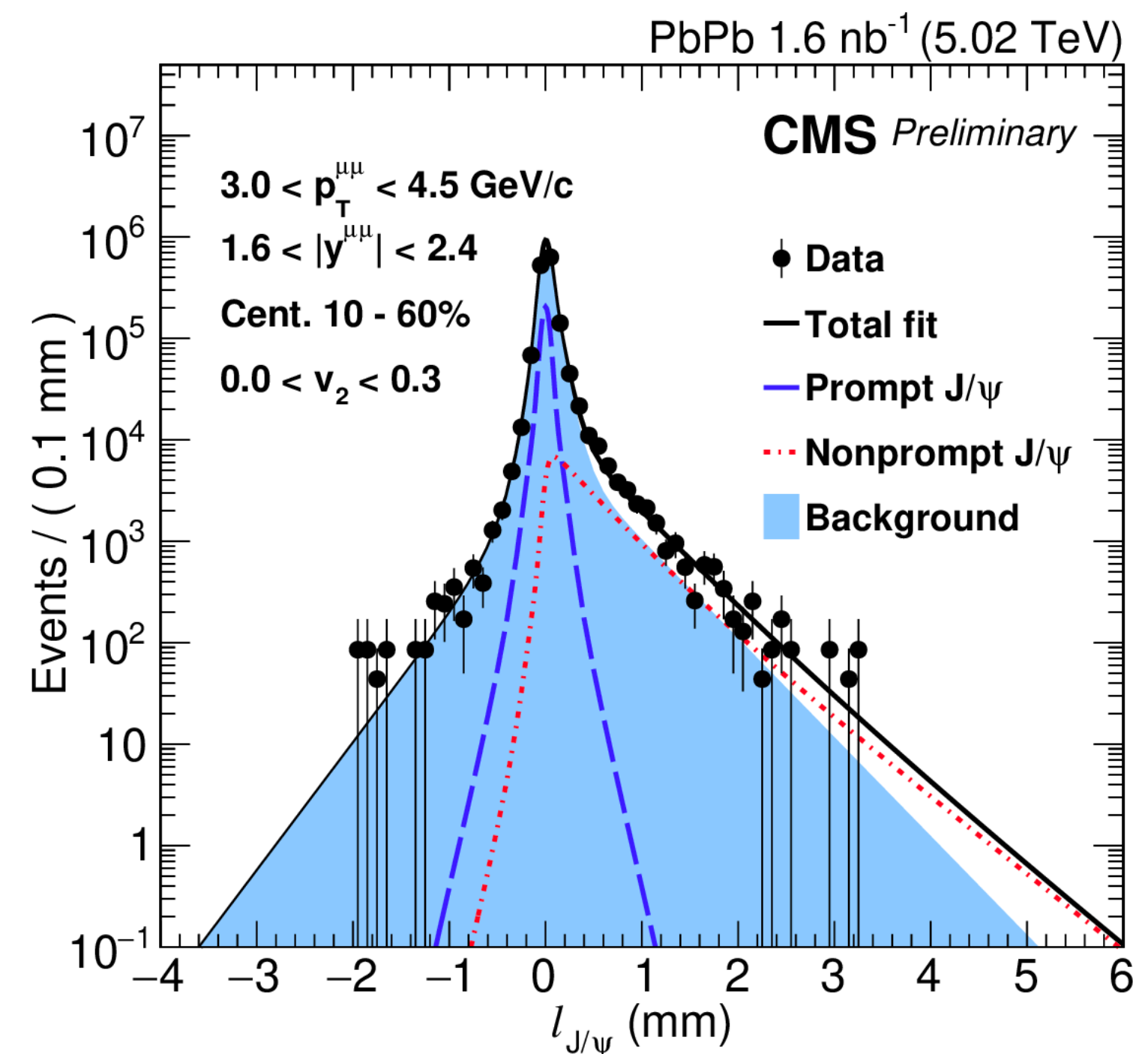
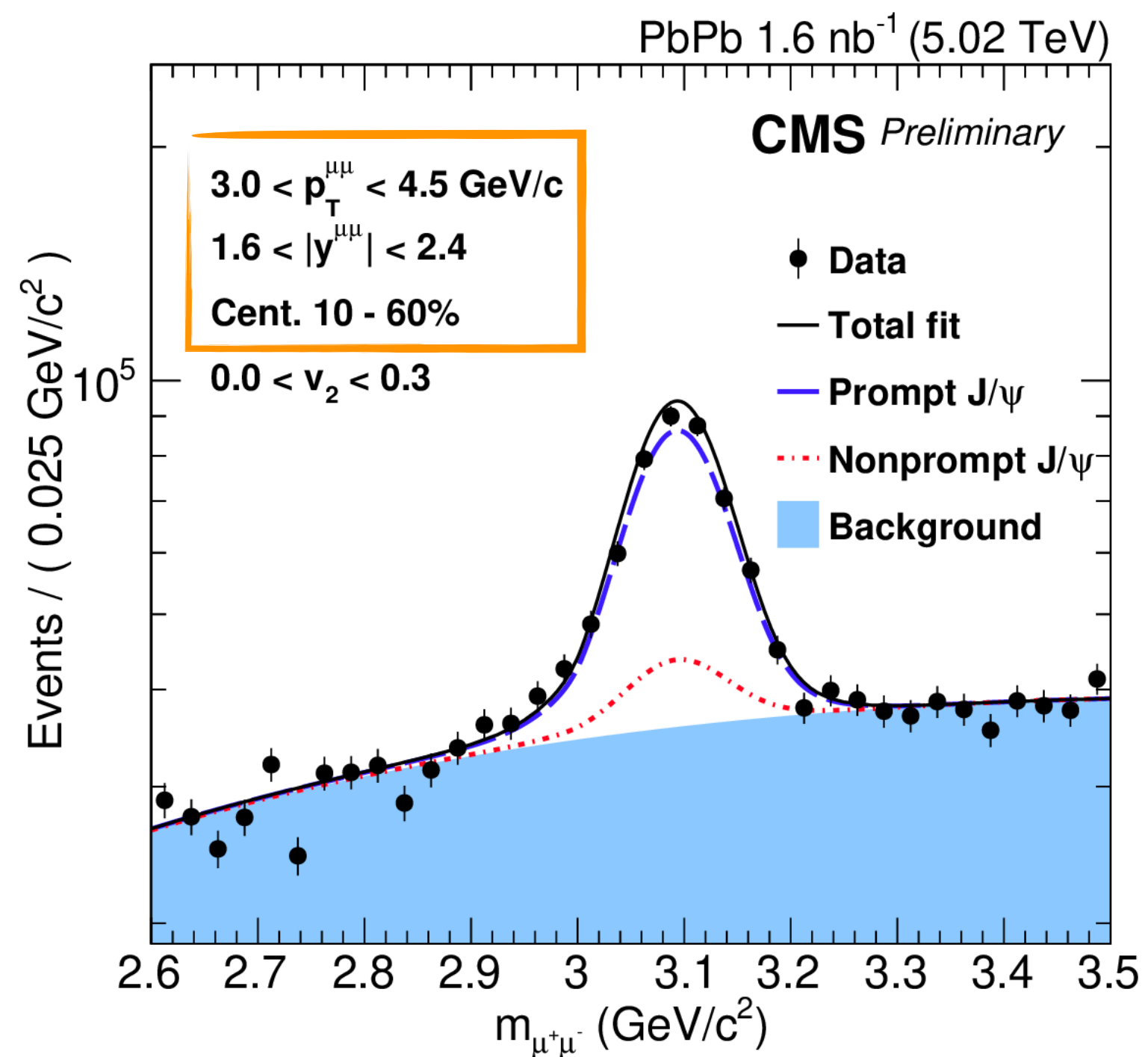
▶  $J/\psi$  measurable down to  $p_T \sim 3$  GeV (forward region) and up to the most central collisions

▶ excellent vertex and muon momentum resolutions

▶ separation of **prompt** and **nonprompt**  $J/\psi$  components

(see Gyeonghwan's talk)

▶ luminosity for rare signals

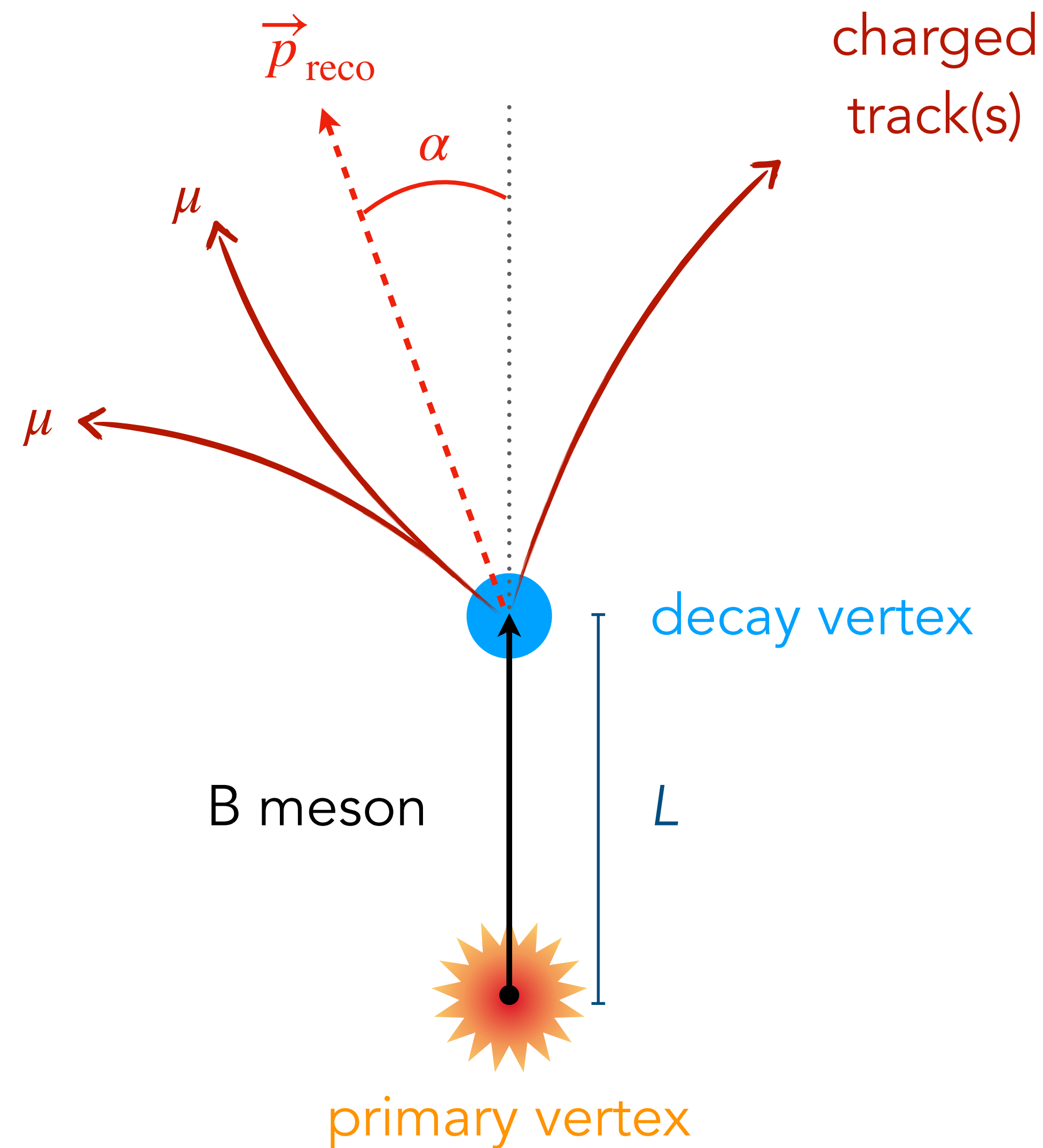


Dimuon distributions in the  $J/\psi$  mass region [PAS-HIN-21-008]

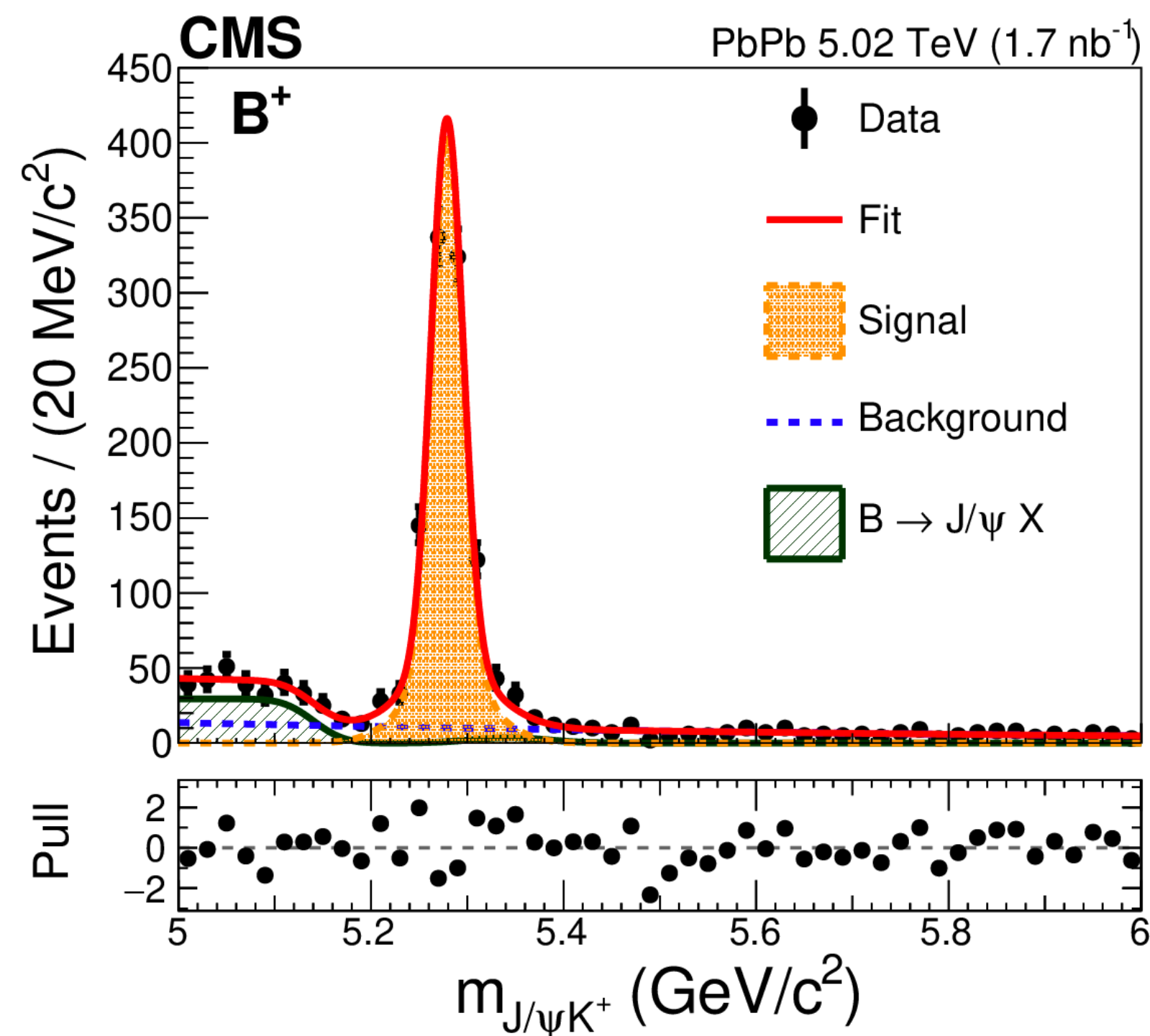
### Exploiting features of B meson decay topology

- ▶ final-state particles from a **common vertex**
- ▶ significance of the **displacement between decay and collision vertices**
- ▶ pointing angle  $\alpha$
- ▶ constraints on particle's  $p_T$
- ▶ + variables specific to each case studied

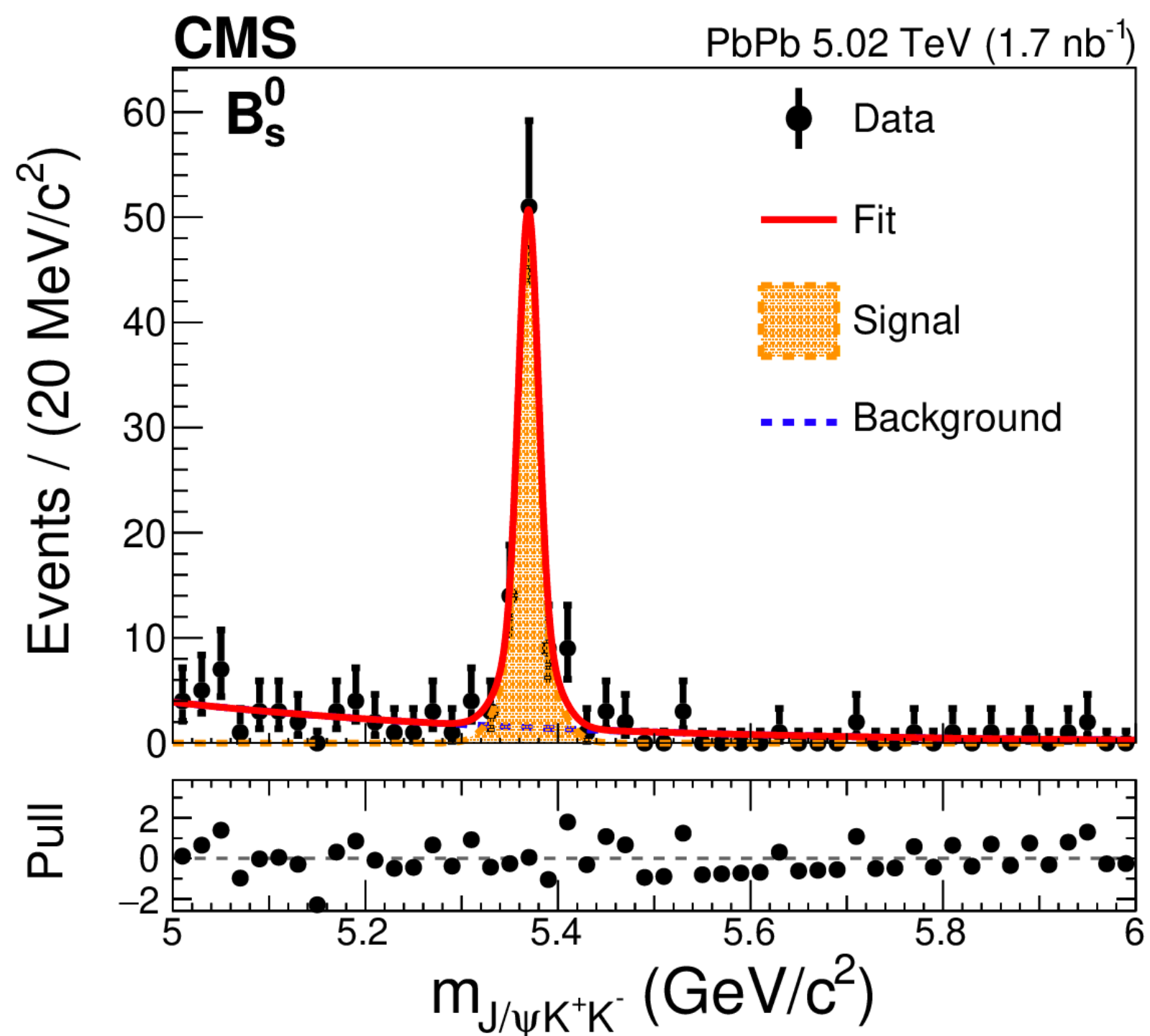
Boosted **D**ecision **T**rees trained with signal MC samples for each B meson separately.



$$B^+ \rightarrow J/\psi (\rightarrow \mu^+\mu^-) K^+$$



$$B_s \rightarrow J/\psi (\rightarrow \mu^+\mu^-) \phi (\rightarrow K^+K^-)$$



**BDT selection**



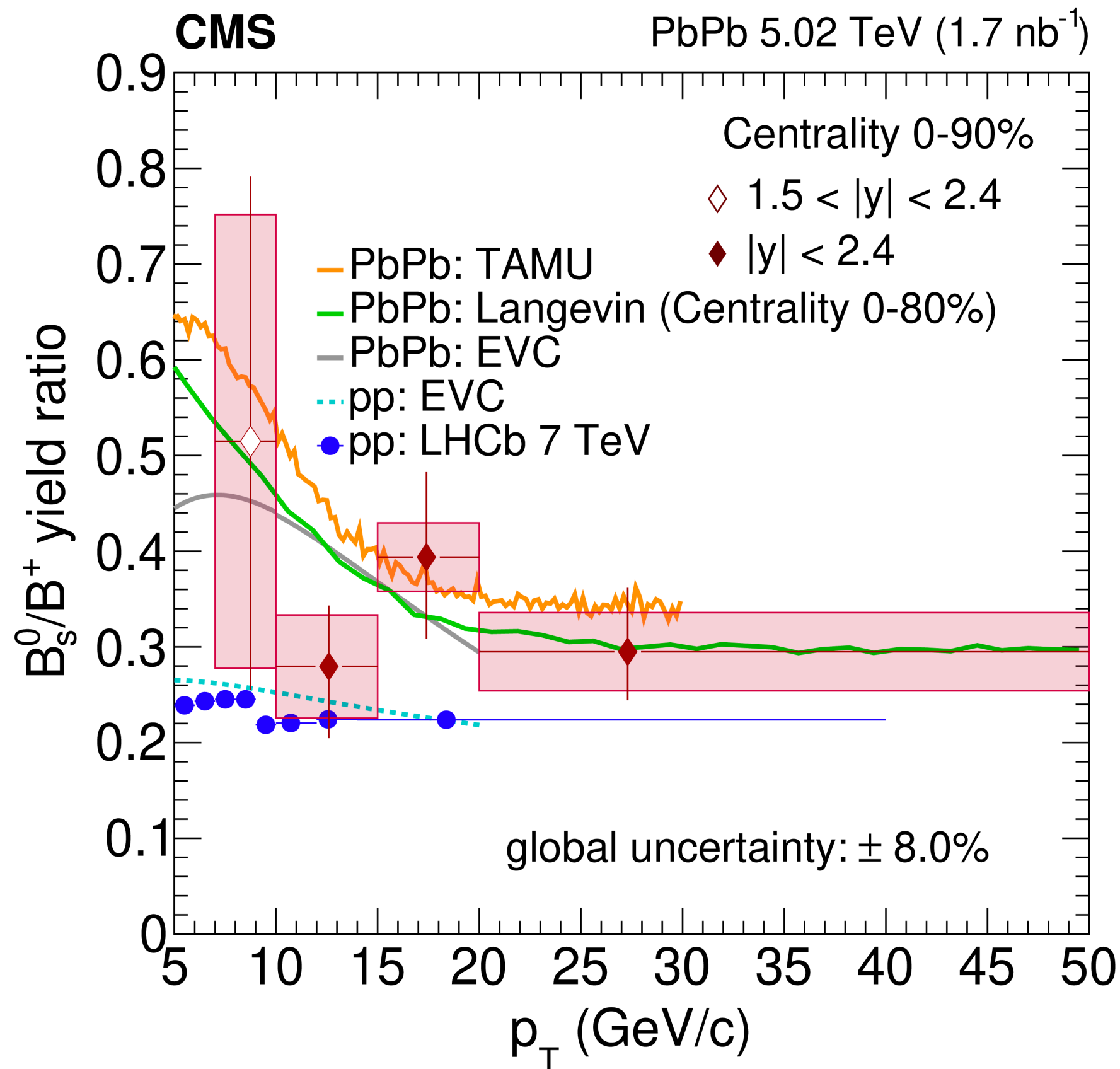
**background rejection  
better than 97%**

**first observation of the  
B<sub>s</sub> meson in heavy ion  
collisions!**

Background contributions

- ▶ uncorrelated combinations of J/ψ candidates with extra particles
- ▶ contaminations from other B decays\* (partially reconstructed decays + misidentified charged tracks)

\*negligible in the B<sub>s</sub> meson case (tight mass selection for the φ candidate)



**PLB 829 (2022) 137062**

Model references

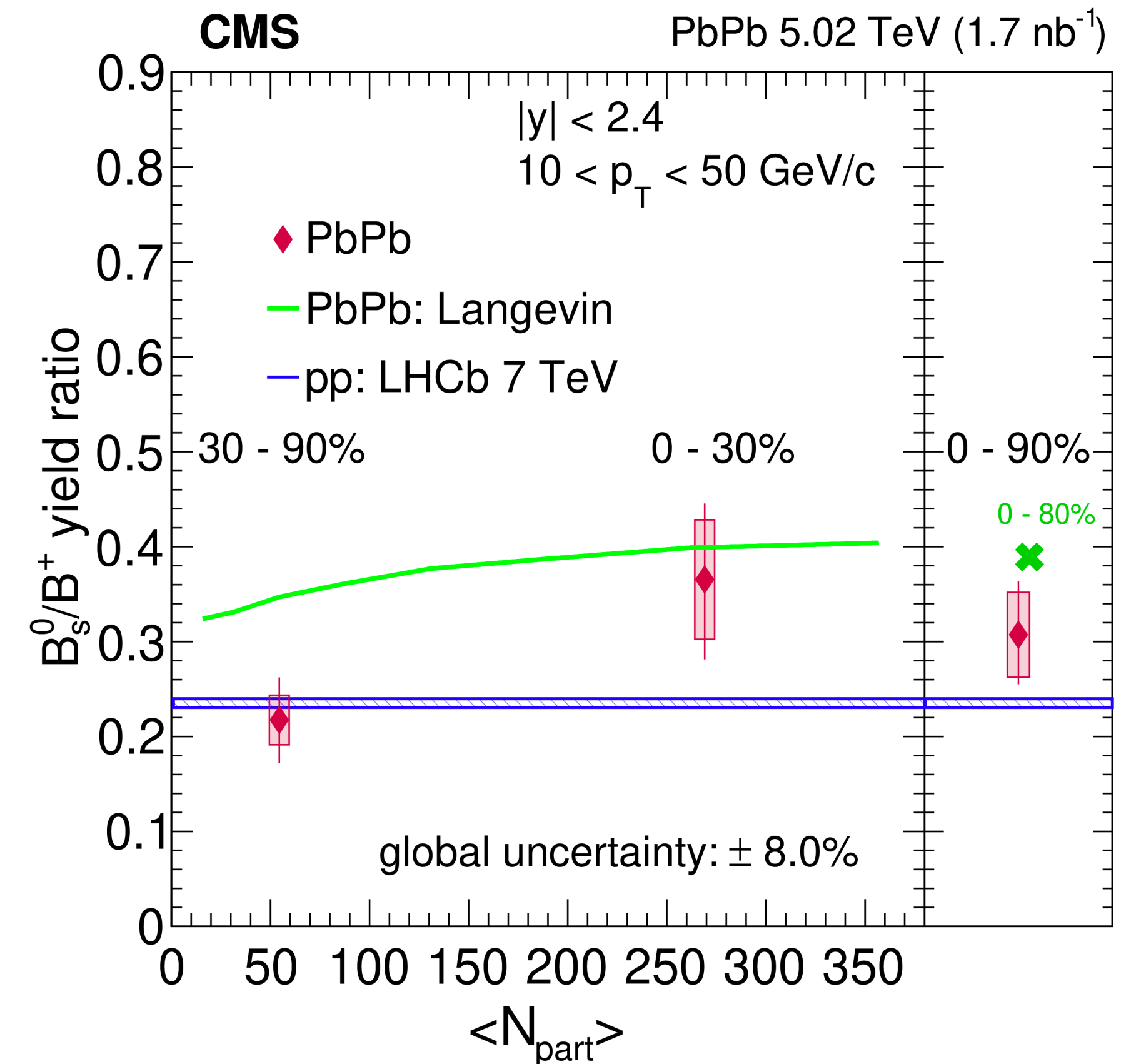
He et al., [PLB 735 \(2014\) 445](#)

Cao et al., [PLB 807 \(2020\) 135561](#)

Song et al., [EPJC 78 \(2018\) 344](#)

LHCb measurement in pp

collisions, [PRL 124 \(2020\) 122002](#)



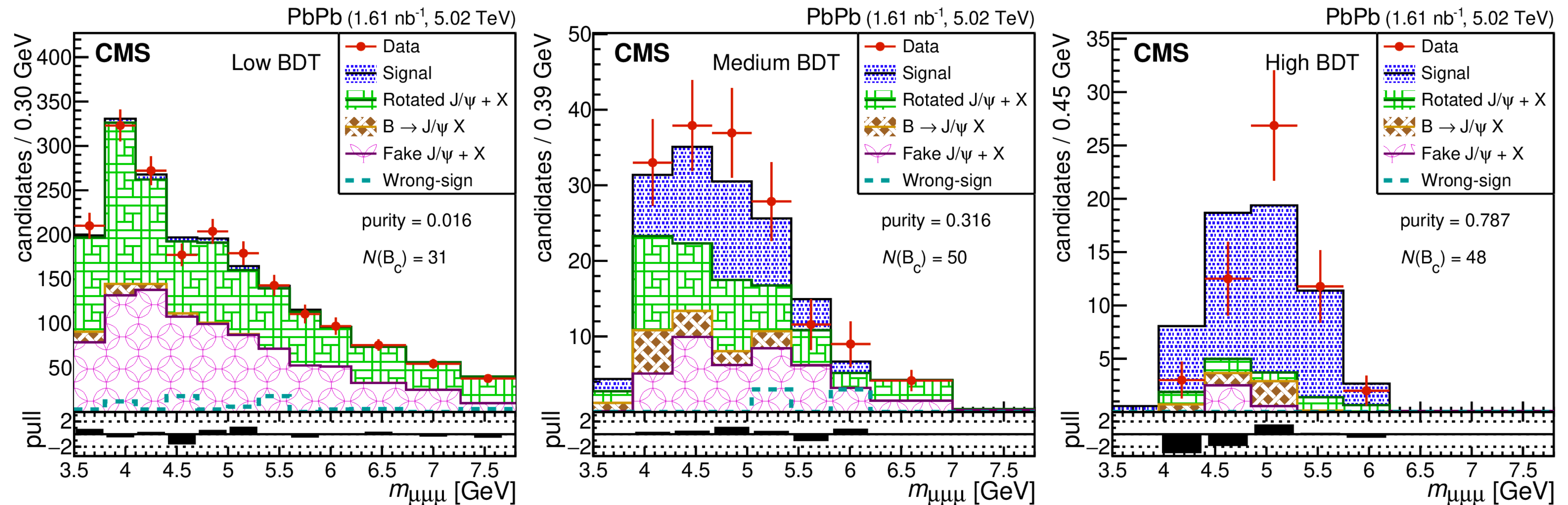
**Measured yield ratios** compatible with predictions from heavy-quark (re)combination models as well as with **pp reference data**

**no significant evidence for enhancement of  $B_s/B^+$  in PbPb collisions** (expected at low  $p_T$ )

- ▶ reconstructed in the decay mode  $B_c^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-) \mu^+ \nu_\mu$
- ▶ **template fit of the trimuon mass** performed simultaneously in three BDT intervals
- ▶ background contributions estimated from data and MC samples

background  
enriched

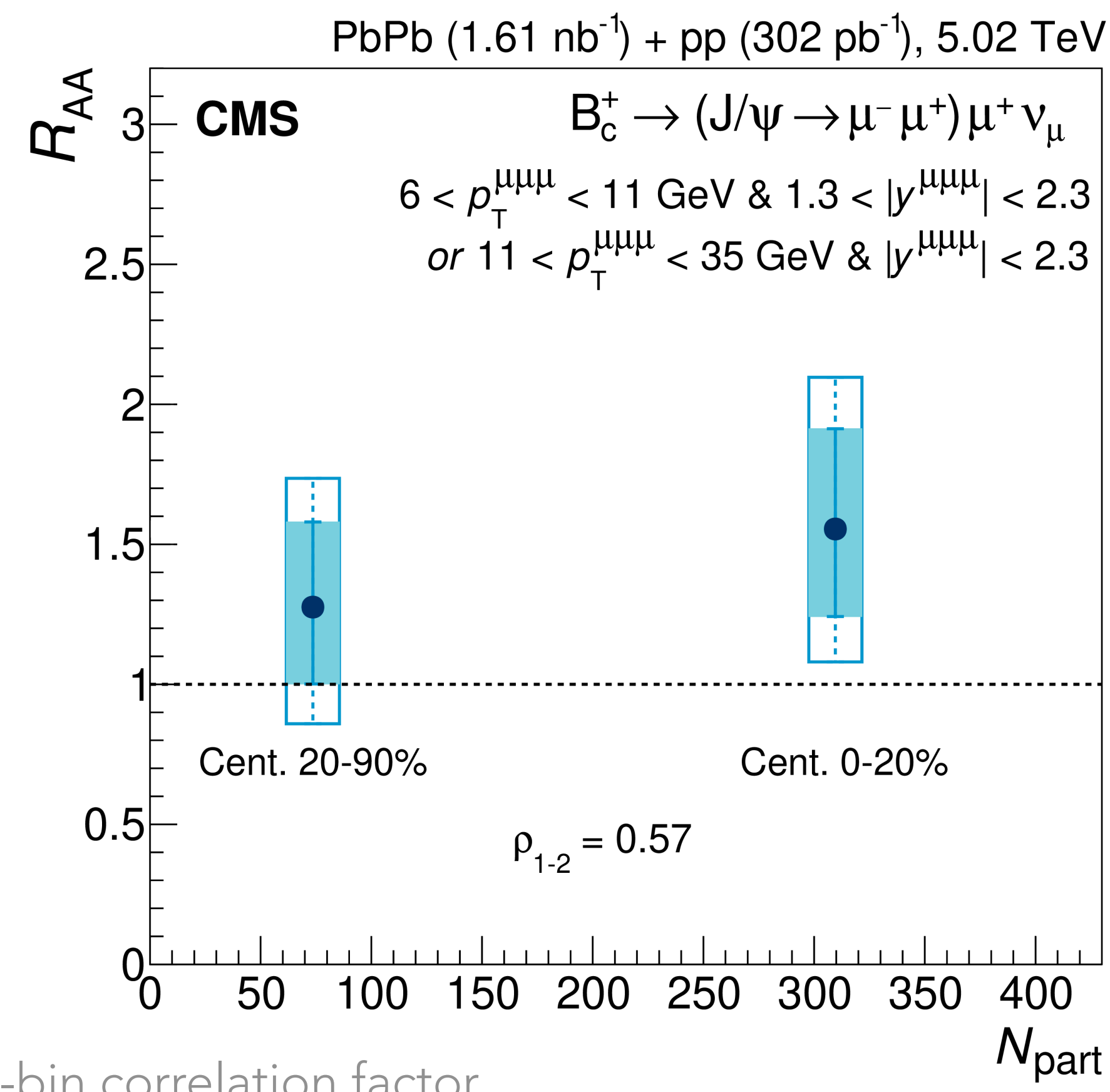
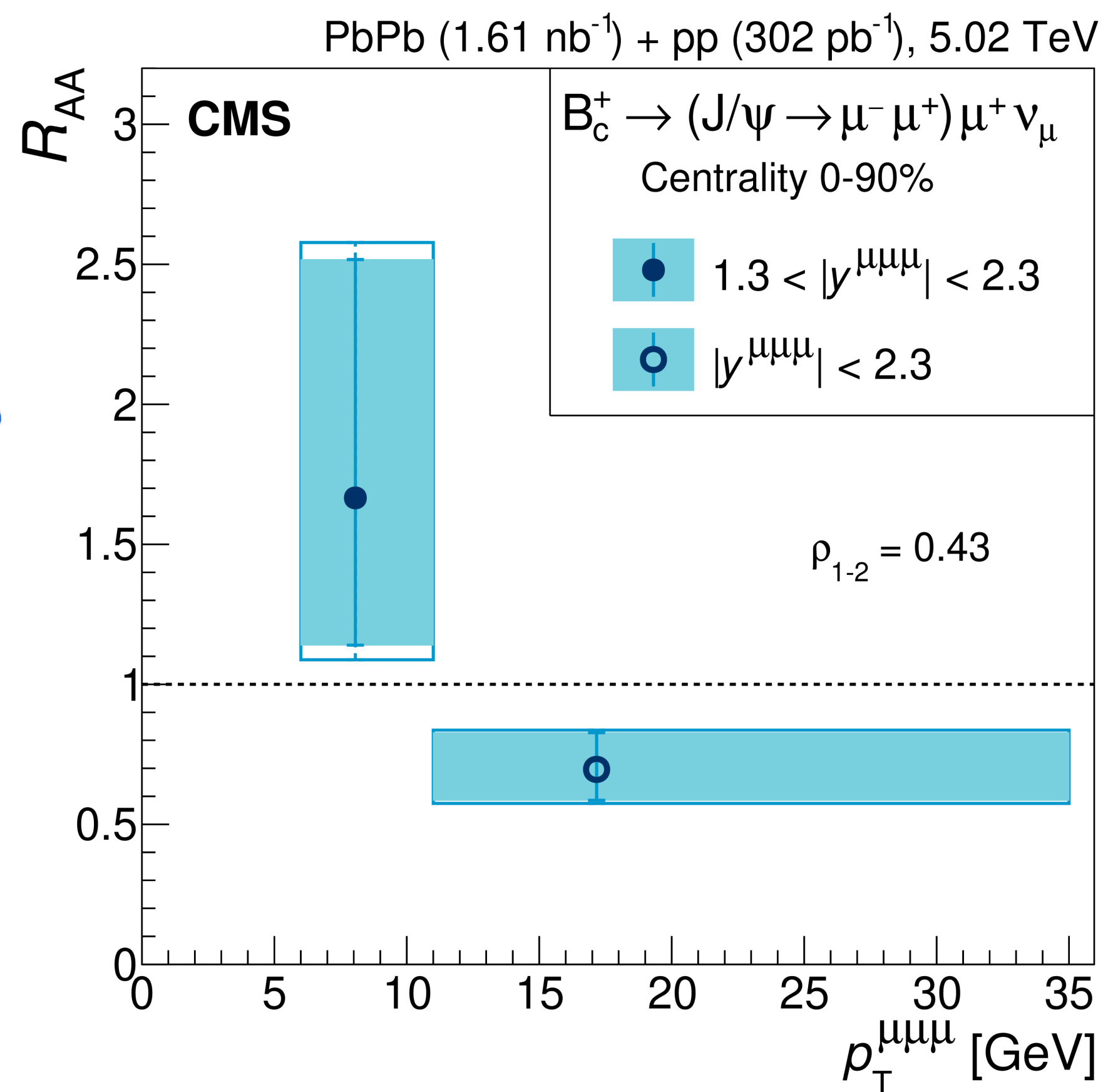
signal  
enriched





- ▶ significant suppression in the high- $p_T$  region
- ▶ low- $p_T$  bin standing above by  $1.8\sigma$
- ▶ hint for a **softer  $p_T$  spectrum** in PbPb collisions

No significant variation as a function of centrality

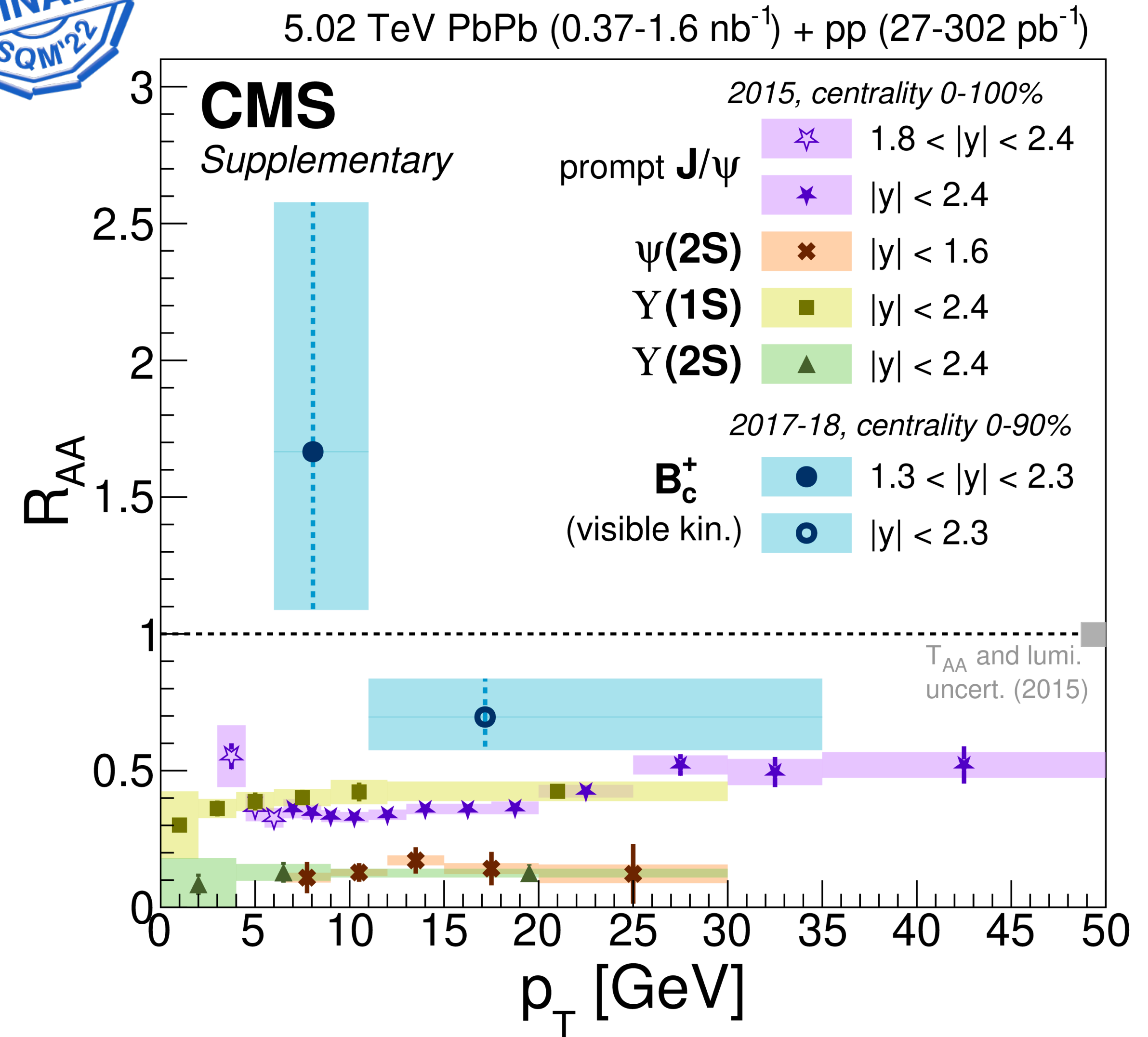


$\rho_{1-2}$ : bin-to-bin correlation factor



Comparison with previous measurements for prompt  $J/\psi$  and  $\psi(2S)$  [EPJC 78 (2018) 509],  $Y(1S)$  and  $Y(2S)$  [PLB 790 (2019) 270]

- ▶  $B_c^+$  less suppressed than quarkonia despite a binding energy between  $J/\psi$  and  $Y(1S)$ 
  - ▶ importance of heavy-quark recombination?
- ▶ Call for first theoretical calculations and more-differential measurement in the future



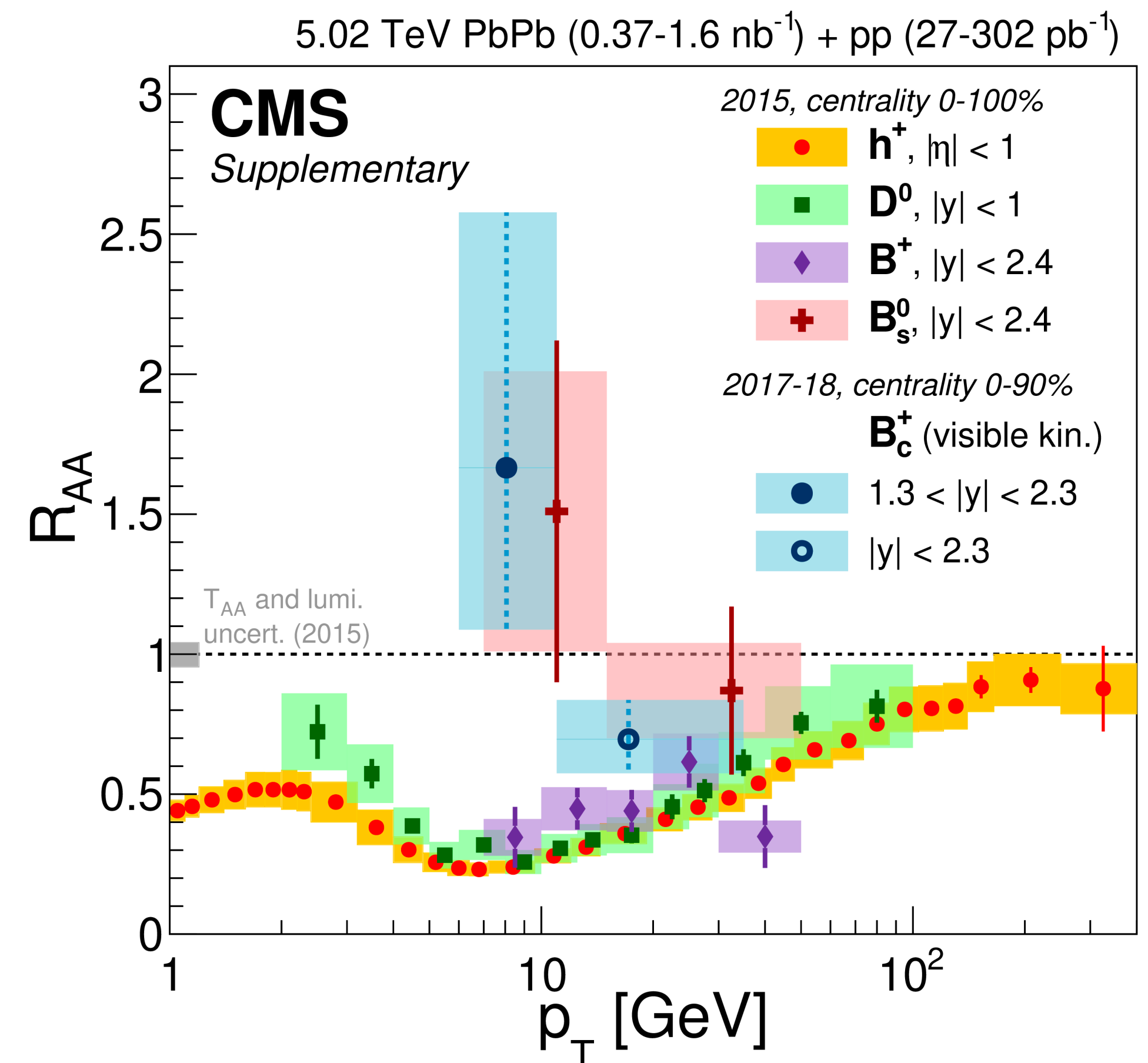
Measurements of beauty flavor hadrons offer new insights into the microscopic QGP properties

- ▶ **first observation of the  $B_s$  and  $B_c^+$  mesons**
- ▶ hint of a weaker suppression than for **light** and other **open heavy flavor hadrons** at low  $p_T$   
+ convergence towards higher momenta
- ▶ no sign of beauty hadronization modification with  $B_s/B^+$
- ▶  $B_c^+$  **less suppressed than quarkonia**

Interpretation of measurements statistically limited

➔ to be continued in Run 3

Compilation of CMS  $R_{AA}$  measurements  
 $h^\pm$ , JHEP 04 (2017) 039;  $D^0$ , PLB 782 (2018) 474  
 $B^\pm$ , PRL 119 (2017) 152301;  $B_s$ , PLB 796 (2019) 168  
 $B_c^+$ , arXiv:2201.02659





**Gluod** *namics*



# Thank you for your attention!

## 관심을 가져주셔서 감사합니다

This in-person presentation is made possible by the financial support of the **France-Korea Particle Physics Laboratory (FKPPL)**



프랑스 FRANCE  
CORÉE 한국



# Supplementary material

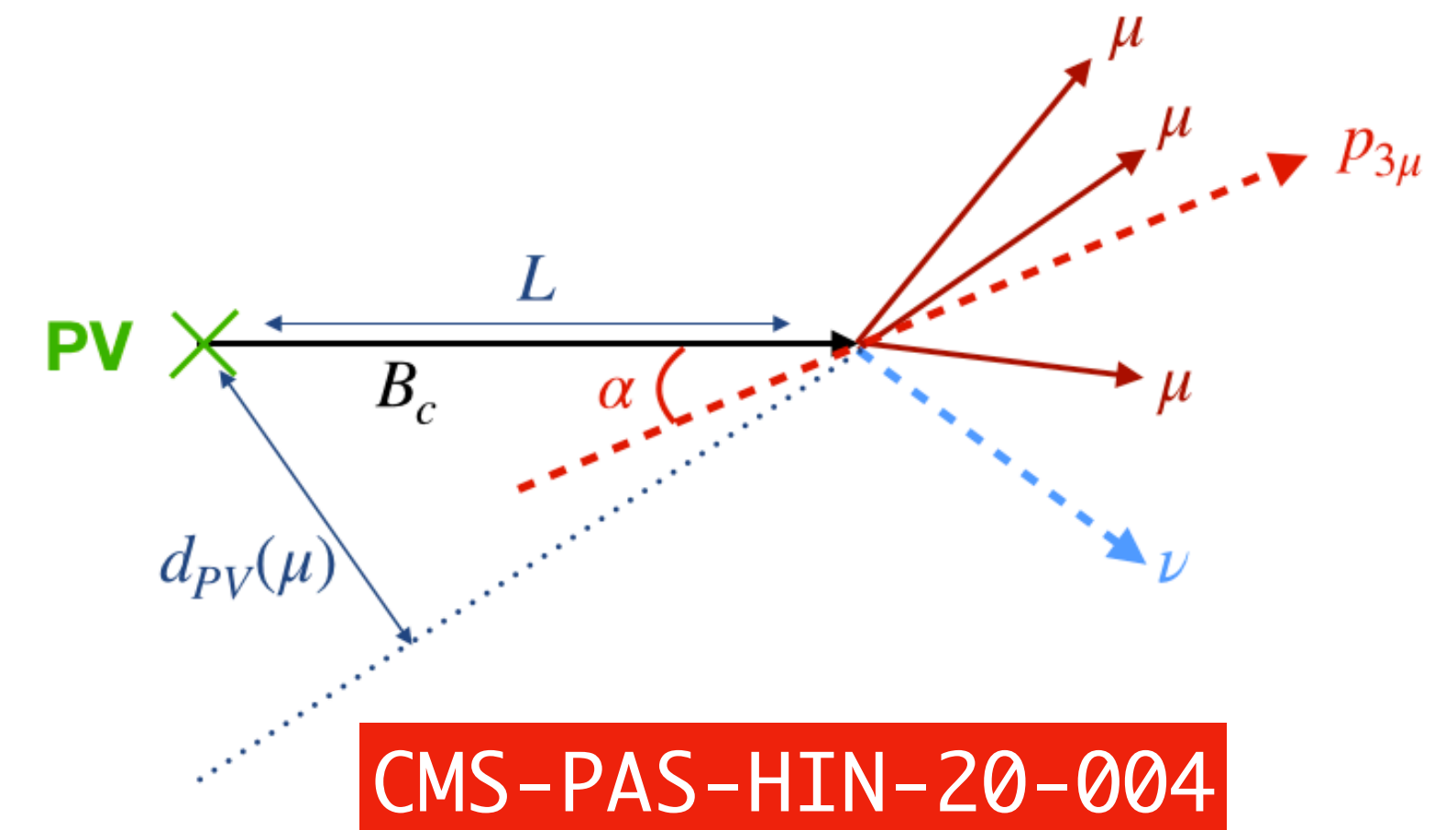


	$B^+$				$B_s^0$			
B meson $p_T$ (GeV/c)	7–10	10–15	15–20	20–50	7–10	10–15	15–20	20–50
Muon efficiency	+7.2	+4.3	+3.8	+3.9	+8.9	+6.0	+3.7	+3.9
	−6.3	−3.9	−3.5	−3.6	−7.5	−5.2	−3.5	−3.6
Data/MC agreement	4.2	15	3.0	1.7	35	5.6	4.7	10
MC sample size	9.1	3.2	1.9	1.4	27	6.3	3.1	3.2
Fit modeling	4.5	2.7	2.8	2.6	1.2	3.8	1.8	6.4
Tracking efficiency	5.0	5.0	5.0	5.0	10	10	10	10
$T_{AA}$			2.2				2.2	
$N_{MB}$			1.3				1.3	
Branching fraction			2.9				7.5	
Total	+15	+17	+8.7	+ 8.2	+47	+17	+15	+18
	−14	−17	−8.5	−8.0	−47	−17	−14	−18

Summary of the systematic uncertainties (relative values in %)

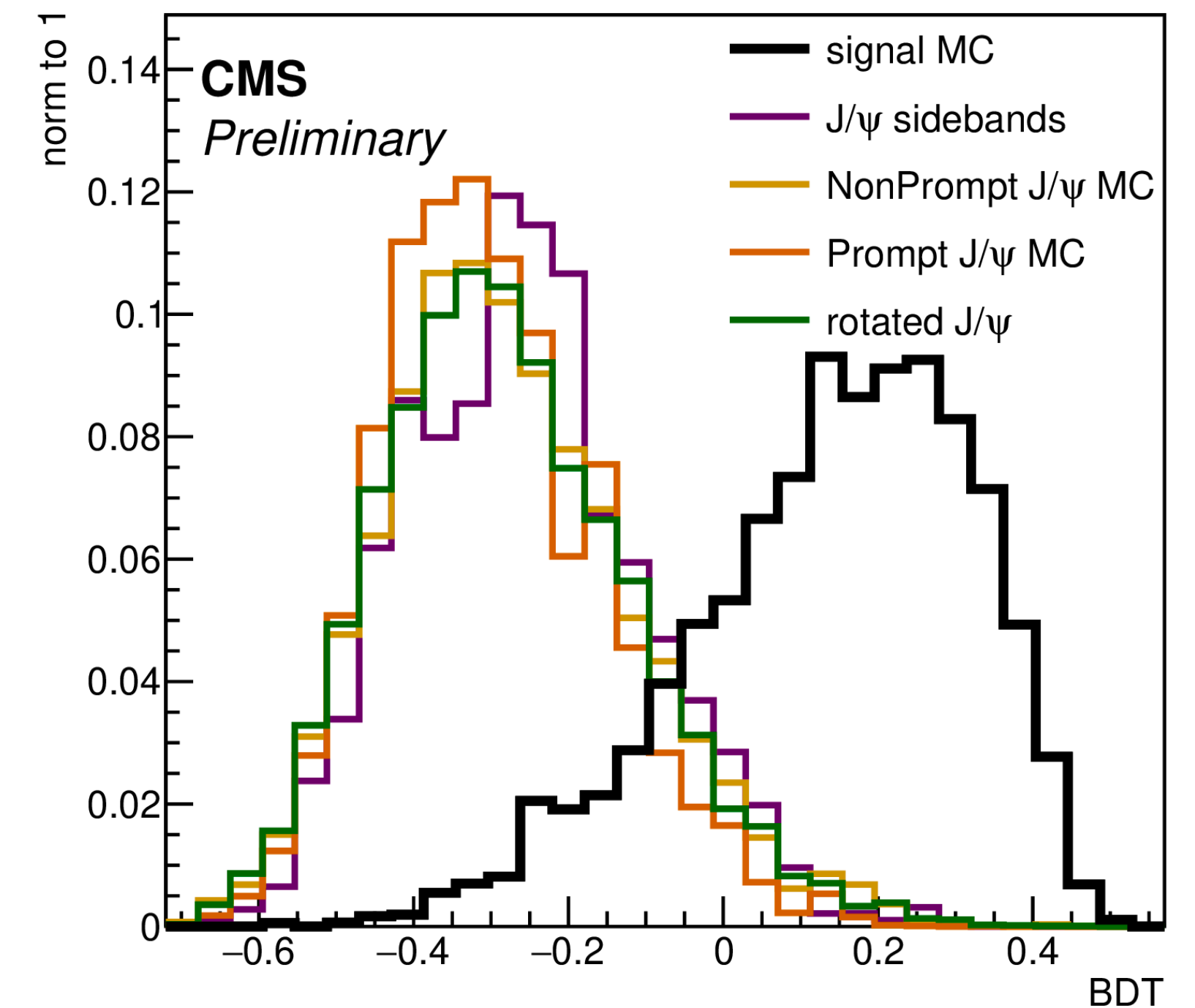
Reconstructed in the decay mode  $B_c^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-) \mu^+ \nu_\mu$

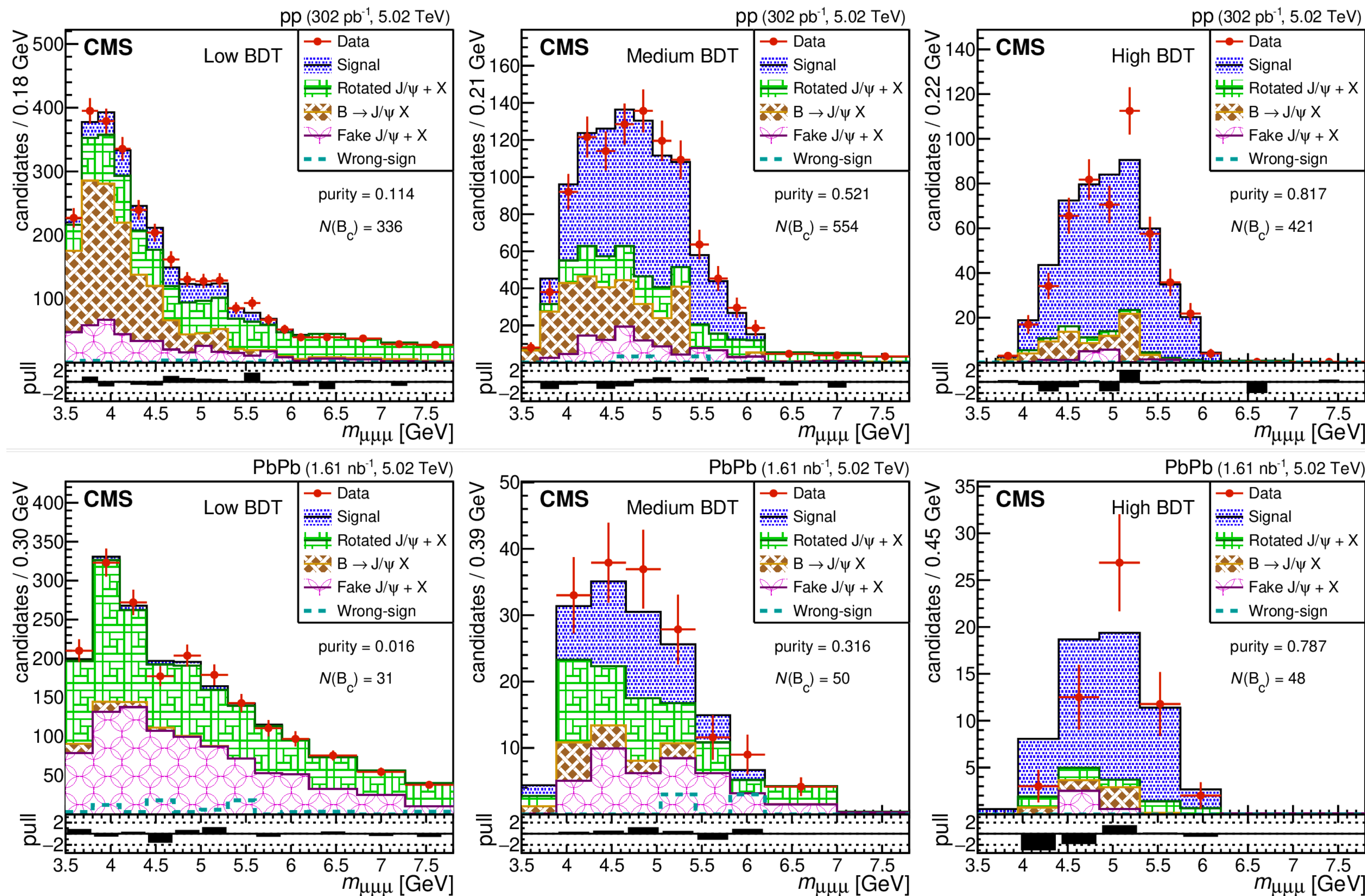
- ▶ **three muons** from a same displaced vertex
- ▶ one opposite-sign pair consistent with the  $J/\psi$  mass
- ▶ trimuon kinematics + wide invariant mass distribution



Signal topology similar to **three background categories**

- ▶ **Fake  $J/\psi$**  = accidental dimuon taken as the  $J/\psi$ 
  - ▶ mass sidebands in data
- ▶ Association of a *true*  $J/\psi$  with a misidentified hadron
  - ▶ nonprompt  $J/\psi$  Monte Carlo ( $B \rightarrow J/\psi + X$ )
- ▶ Combination of a  $J/\psi$  and a muon from different vertices
  - ▶ decorrelation by rotating the  $J/\psi$  candidates around the PV before association with muons (data)





pp data

Background components

- ▶ rotated  $J/\psi$  data sample
- ▶ nonprompt  $J/\psi$  MC
- ▶ wrong  $J/\psi$  candidate (data dimuon sidebands)
- ▶ pure combinatorial background from three same-sign muons

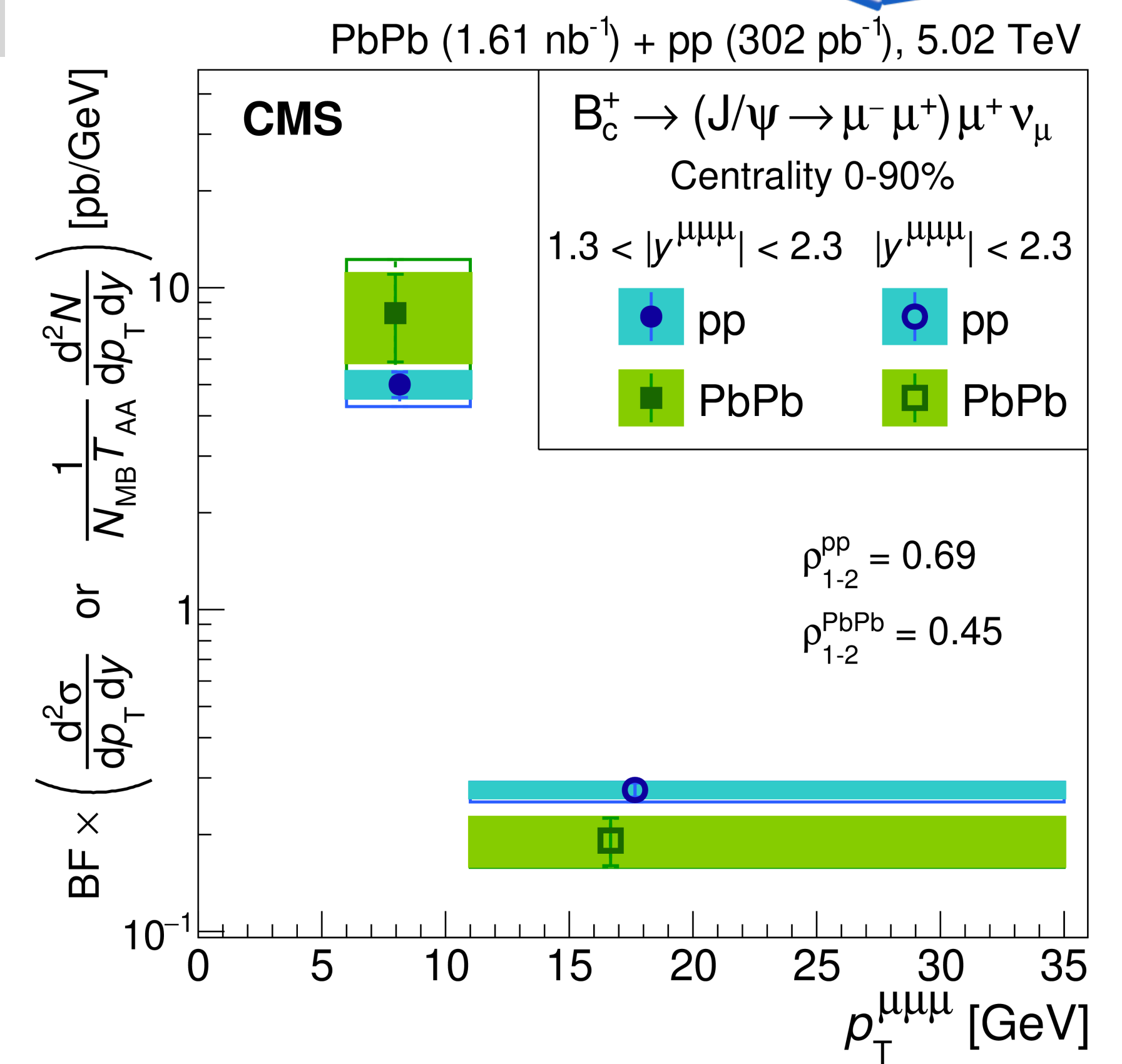
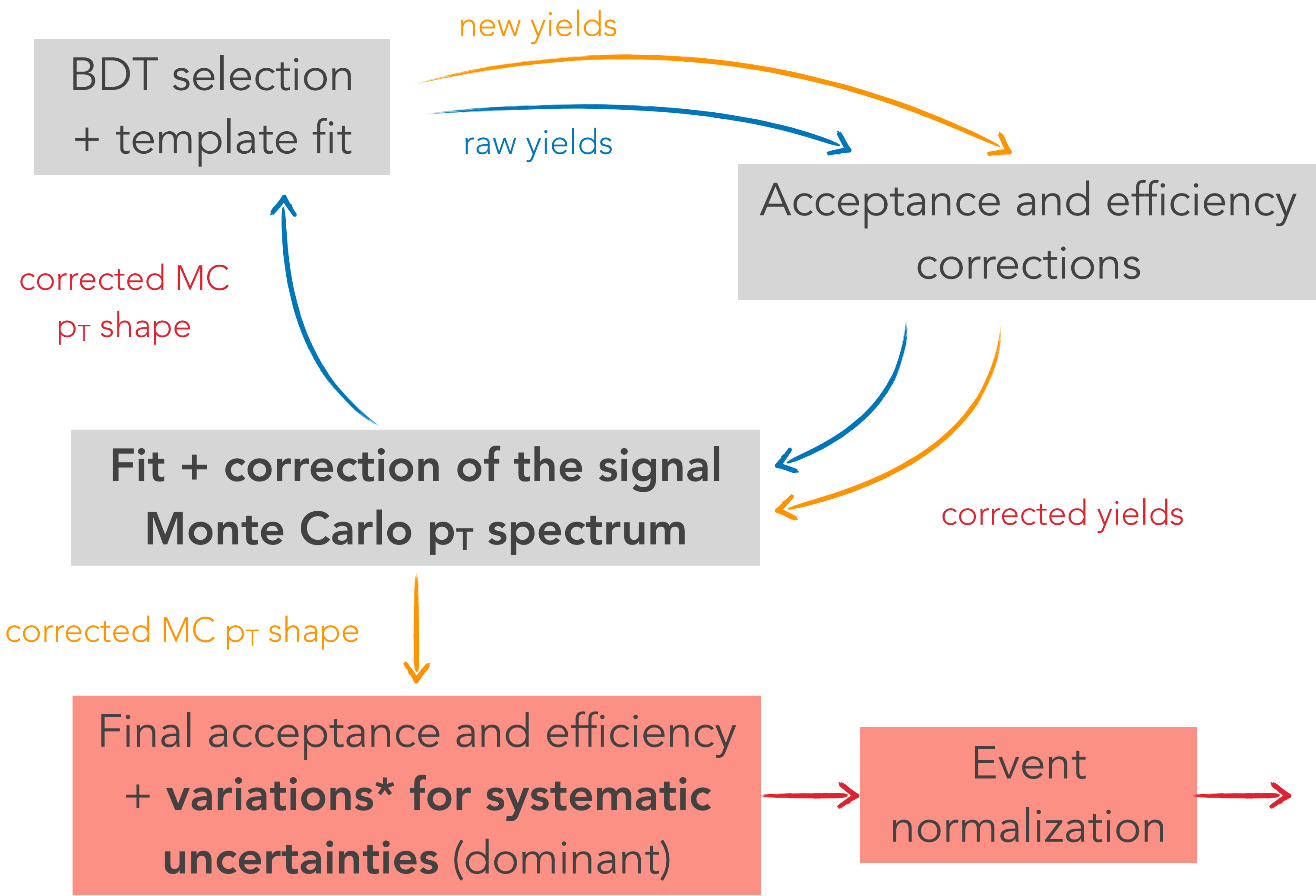
PbPb data



arXiv:2201.02659



Analysis workflow  
 first step  
 second step  
 output / result



\*account for correlations with other uncertainties (template fit shapes, ...)

$\rho_{1-2}$ : bin-to-bin correlation factor