Hadronization and Energy Loss of Beauty Quark from Flavor-identified B-Hadrons RAA in pp, pPb, and PbPb Collisions with CMS

Hard Probes 2024

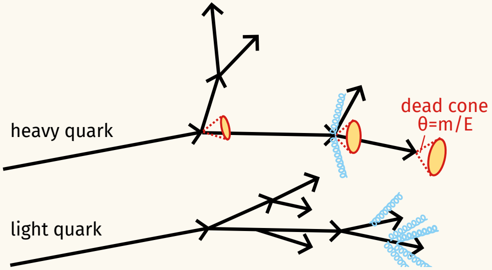
Tzu-An Sheng
for the CMS Collaboration

Sep. 24 2024

Laboratory for Nuclear Science

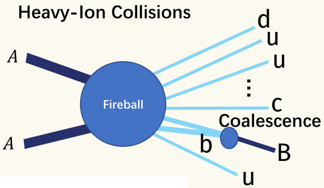
B mesons probes the properties of QGP

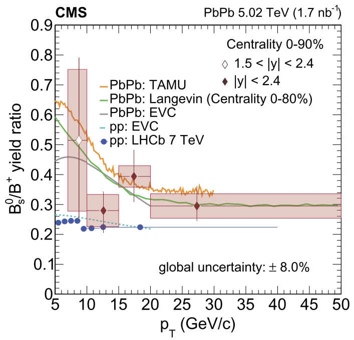
- Mass dependence of parton energy loss
  - Dead-cone effect: less radiative energy loss for heavier quarks
  - See Lida Kalipoliti's talk (Sep 25, 9:40) for the dead-cone effect in CMS b-jet
- Beauty diffusion coefficient
  - Brownian motion of b quark in the medium
- CMS has the unique advantage to measure exclusive B meson decays in AA systems

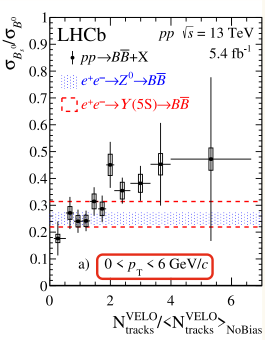


Coalescence and strangeness enhancement with B mesons

- Hadronization: in addition to fragmentation, b quarks also recombine with nearby constituent quarks into hadrons
- Enhanced B_s^0 R_{AA} compared to B^+ expected at low p_T



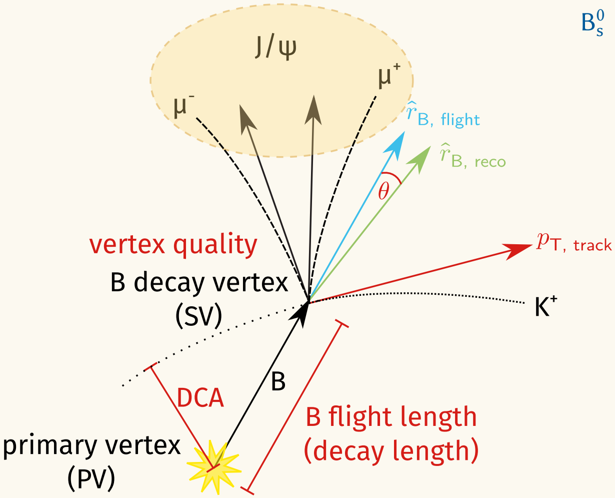




PLB 829 (2022) 137062

PRL 131 (2023) 061901

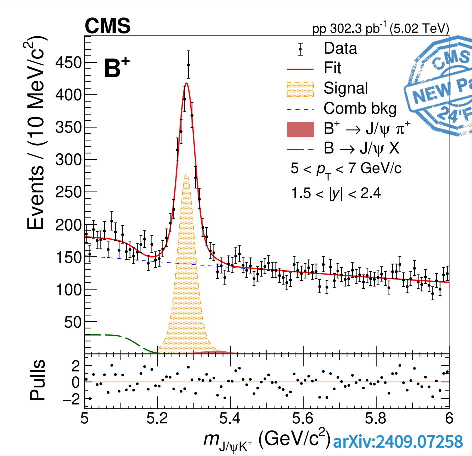
B_s^0 / B^+ event selection

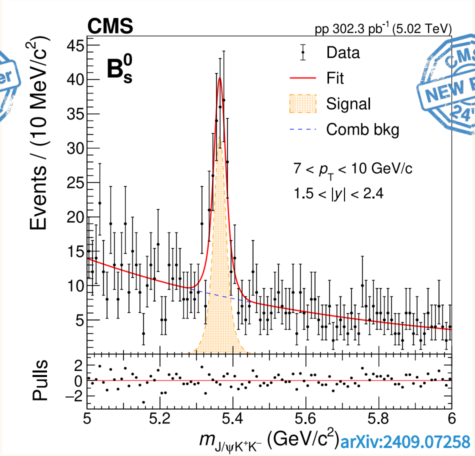


$B^+ \to J/\psi K^+ \to \mu^- \mu^+ K^+$
$B_s^0 \to J/\psi \phi(1020) \to \mu^- \mu^+ K^+ K^-$

- Long-lived B mesons
  → large decay length significance
- Angle between B flight direction and PV-SV displacement
  $\cos\theta = \hat{r}_{\text{B, flight}} \cdot \hat{p}_{\text{T, RECO}}$
  Expect $\hat{r}_{\text{B, flight}} \parallel \hat{p}_{\text{T, RECO}}$
- χ^2 Probability of the decay vertex
- p_T of the daughter tracks
- Track DCA (in z and x-y direction)

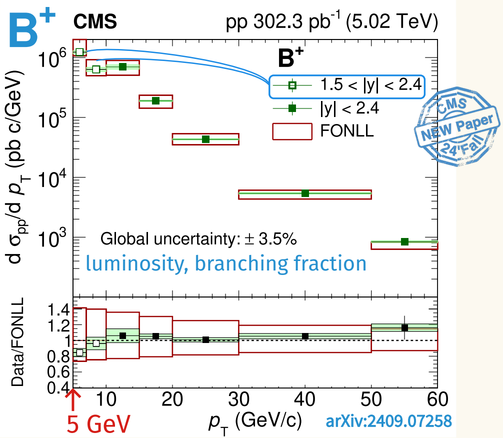
B_s^0 / B^+ Yield extraction

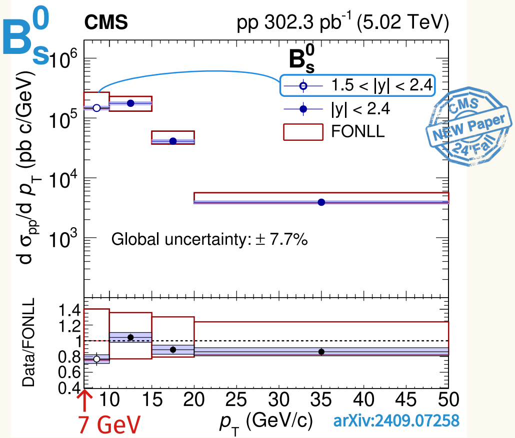




- B^+ (semi-)peaking background:
  - Error function: Partially reconstructed B decay (e.g. $B^0 \to J/\psi(K^* \to K^+\pi^-)$)
  - Double bifurcated Gaussian: misidentified π in $B^+ \to J/\psi\pi^+$

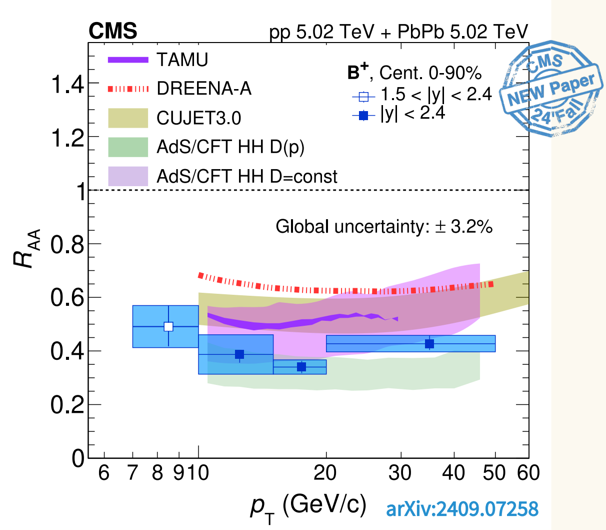
Cross sections in pp collisions





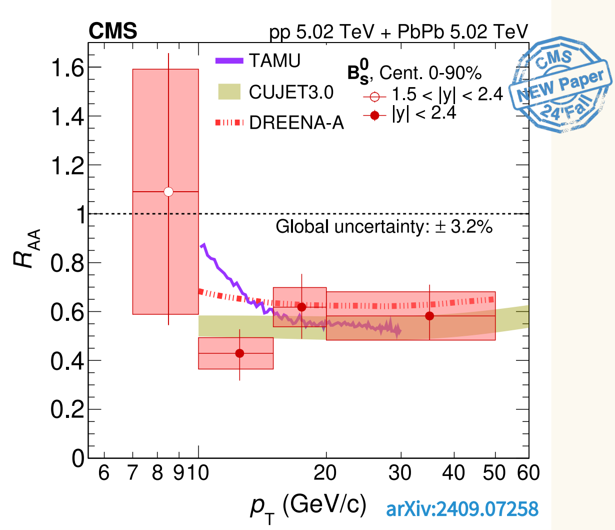
- Larger cross section at lower p_T, consistent with FONLL calculation
- Kinematic constraints to go down to lower p_T
- Dominant systematics from difference between MC and Data

B^{+} R_{AA} compared with theory



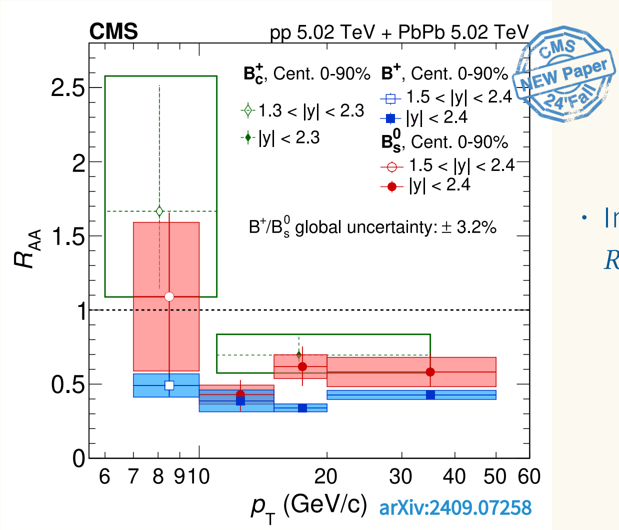
- DREENA-A, CUJET3.0: (perturbative QCD) collisional and radiative energy loss
- TAMU: (transport model) collisional energy loss
- AdS/CFT HH: thermal fluctuations in the energy loss; diffusion coefficient dependence on quark momentum
- Provides constraining power on the mechanism of beauty quark energy loss and hadronization

B_s^0 R_{AA}



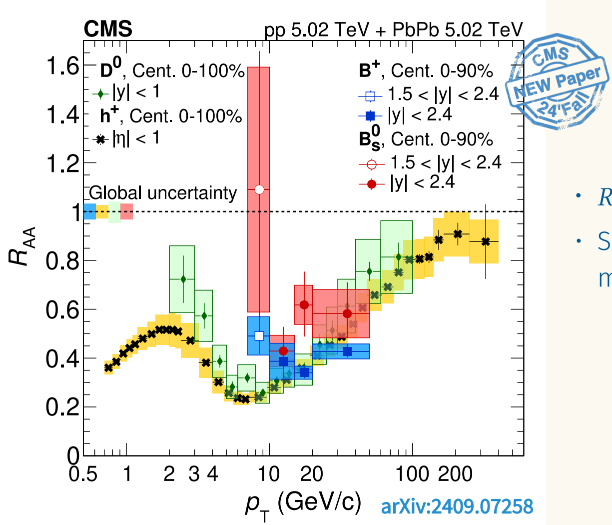
- $p_T < 15$ GeV:
  - TAMU: includes recombination
  - CUJET3.0: doesn't include recombination
- Roughly compatible with all 3 theory predictions within uncertainty

B mesons R_{AA} compared to B_c^+



- Indication of mass ordering:
  $R_{AA}(B_c^+) > R_{AA}(B_s^0) > R_{AA}(B^+)$

B mesons R_{AA} compared to light flavors

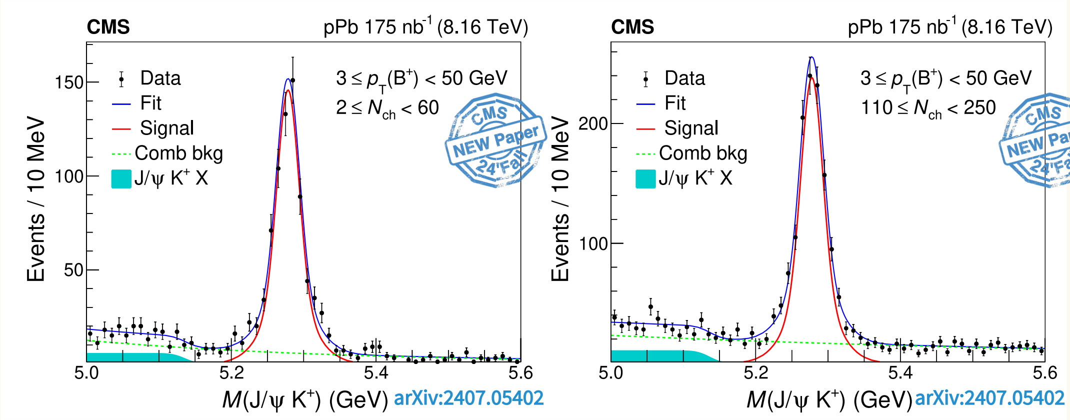


arXiv:2409.07258

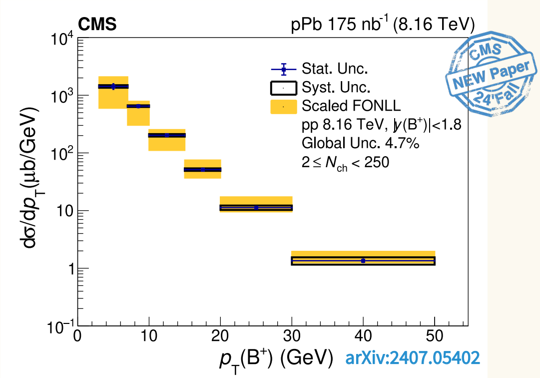
- R_{AA} converge at high p_T
- Splitting between B and D^0 at low p_T: mass hierarchy

Bridging the gap: B^+ production in the pPb system

B^+ yield extraction in pPb

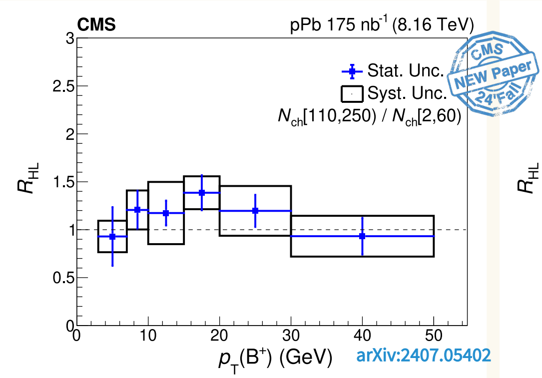


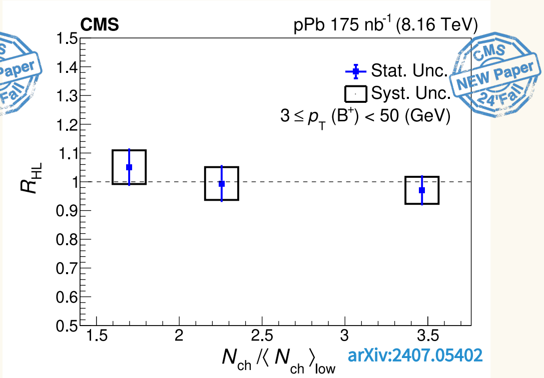
B^+ $d\sigma/dp_T$ in pPb agrees with FONLL



- Much smaller uncertainties than FONLL
- FONLL uncertainties: renormalization and factorization scales, b mass, parton distribution functions

$R_{HL}(B^+)$ in pPb

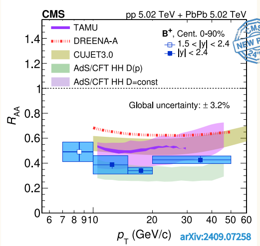




$$R_{HL} = \frac{\langle N_{coll} \rangle|_{low}}{\langle N_{coll} \rangle|_{high}} \frac{(d\sigma/dp_T)|_{high}}{(d\sigma/dp_T)|_{low}}$$

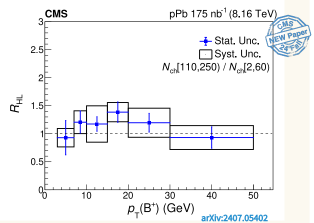
Summary

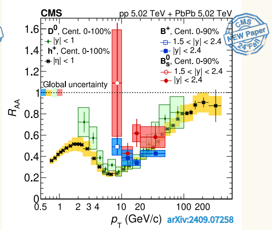
- Measured B meson cross section down to 5 GeV and R_{AA} down to 7 GeV
- Improved precision of the B^+ and B_s^0 meson R_{AA}
- (B^+) Able to distinguish different models based on the new accuracy
- A trend of B_s^0 R_{AA} larger than B^+ R_{AA}
- B meson R_{AA} larger than D^0 and light flavor at $p_T < 10$ GeV
- First B^+ measurement in pPb as a function of N_{ch}



MIT HIG group's work is supported by US DOE-NP

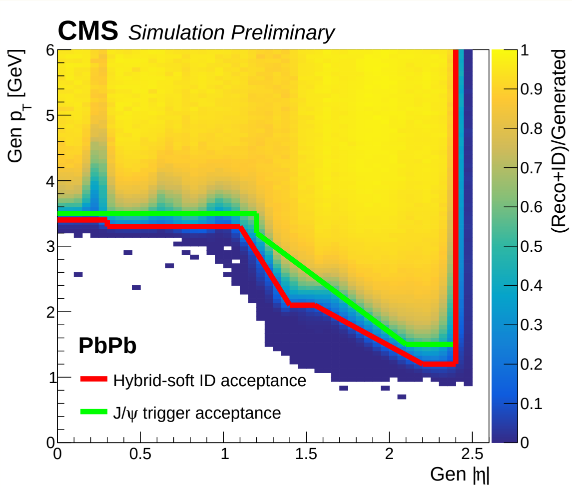
U.S. DEPARTMENT OF ENERGY

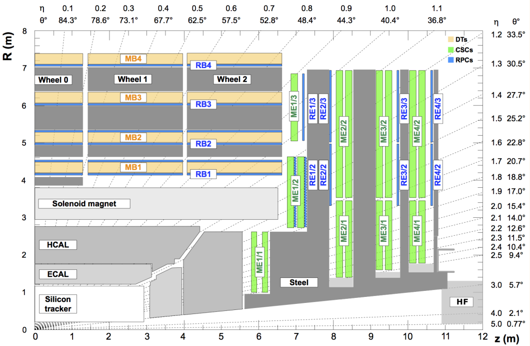




Backup

Muon acceptance





- Acceptance: material, magnetic field

Systematic uncertainties

Source	p_T (GeV/c) 5–7	7–10	10–15	15–20	20–30	30–50	50–60	20–50
Hadron tracking efficiency	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Track selection	1.8	0.31	0.43	0.37	0.27	0.052	1.6	0.24
Data-MC discrepancy	4.7	7.2	7.2	0.98	0.87	0.92	0.83	0.84
p_T shape	0.02	0.0054	0.013	0.0095	0.0047	0.0032	0.018	0.0031
PDF variation	2.1	1.4	3.2	1.1	0.69	1.8	2.4	0.57
Muon efficiency	0.47	0.45	0.37	0.36	0.43	0.64	0.64	0.47
Bkg contamination of efficiency	1.5	2.8	0.84	0.41	0.46	0.18	1.1	0.41
Sum	6.2	8.3	8.3	2.9	2.7	3.2	4.1	2.7
Luminosity $\mathcal{L}$	1.9							
Branching fractions	2.9							
Sum (global systematics)	3.5							

p_T (GeV/c) 7–10	10–15	15–20	20–50
4.8	4.8	4.8	4.8
0.65	0.2	2.7	0.78
3.7	1.9	1.7	1.5
0.045	0.015	0.0037	0.0024
3.6	2	2.9	3.2
0.46	0.38	0.35	0.45
1.1	2.3	0.28	0.38
7.2	6	6.5	6
1.9			
7.5			
7.7			

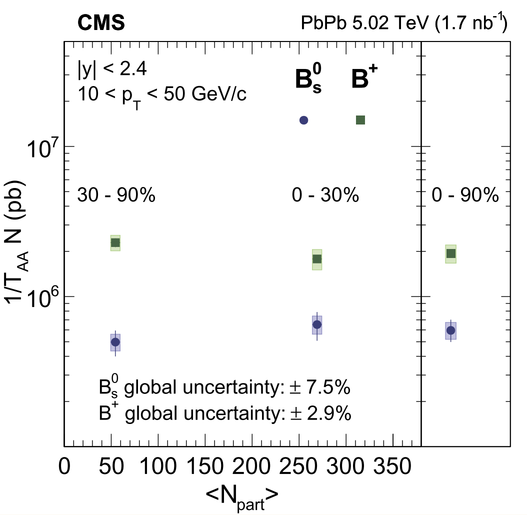
- Tracking efficiency: 2.4% per track
- Dominant systematics from inaccurate description of MC (especially DLS)

Data-averaged 2D map efficiency correction

$$\left\langle \frac{1}{\alpha(p_{\mathrm{T}}, y) \times \varepsilon(p_{\mathrm{T}}, y)} \right\rangle = \frac{\sum_{i,j}^{N_i,N_j} \frac{1}{\alpha(p_{\mathrm{T}},y)\varepsilon_{i,j}(p_{\mathrm{T}},y)} n_{i,j}(p_{\mathrm{T}}, y)}{\sum_{i,j}^{N_i,N_j} n_{i,j}(p_{\mathrm{T}}, y)},$$

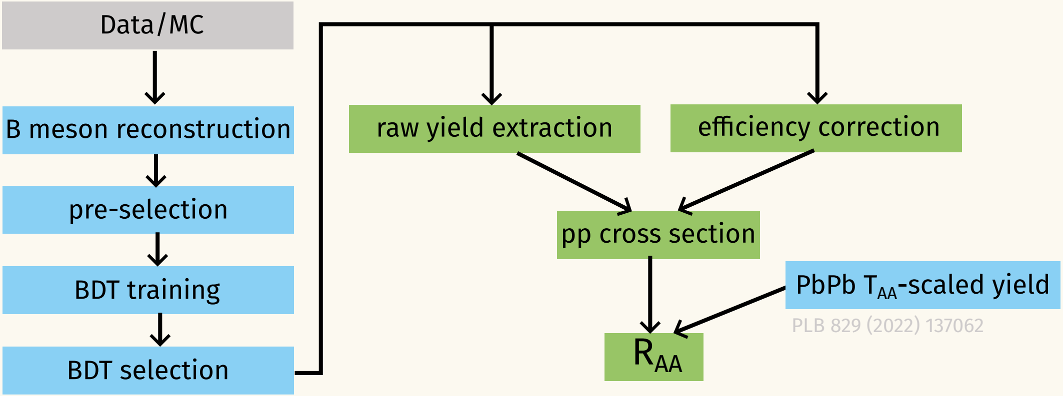
- Independent of the p_{T} distribution from MC
- Account for the correlation between p_{T} and y
- Regularize the distribution by taking the inverse of the total efficiency

Multiplicity dependence in PbPb yield



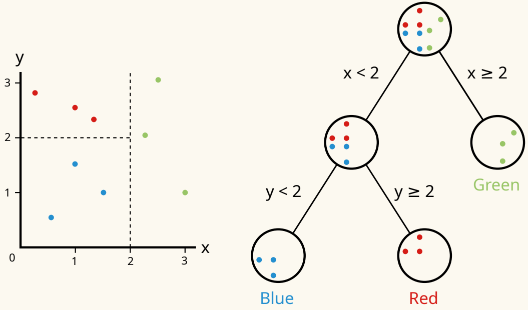
PLB 829 (2022) 137062

Analysis procedure



Cut optimization

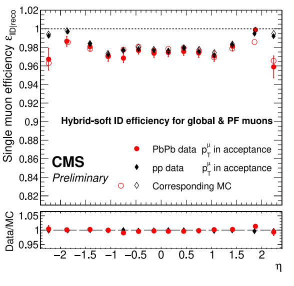
- Maximize the discriminating power by training a machine learning algorithm in the multi-dimensional parameter space.
- Boosted Decision Tree (BDT):
  - Select on each variable sequentially in a tree structure
  - Train many weak classifiers with subsets of randomly selected samples, emphasizing the misclassified events

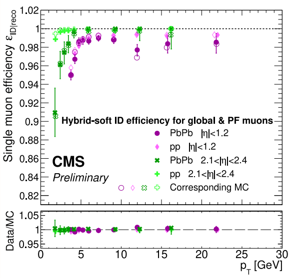


B_s^0/B^+ production yield calculation

$$\frac{d\sigma_{pp}}{dp_T} = \frac{1}{2}\frac{N_{obs}(p_T)}{\mathcal{B}\,\mathcal{L}}\frac{1}{\Delta p_T}\left\langle\frac{1}{\alpha(p_T,y)\,\epsilon(p_T,y)}\right\rangle,$$

- Acceptance and efficiency corrected using a fine (p_T, y) 2D map
- Muon efficiency corrected by data/MC scale factors using J/ψ





CMS-PAS-MUO-21-001