Statistical Production of B_c Mesons in Pb-Pb Collisions at the LHC energy

Based on S. Zhao & MH, arXiv:2407.05234

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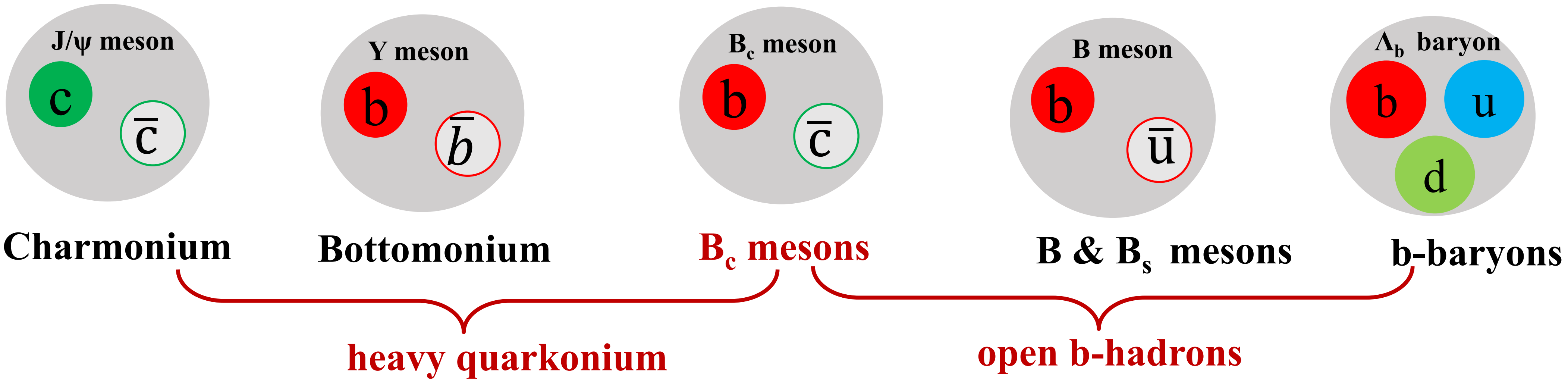
Charmonium, bottomonium & B_c mesos

- Heavy quark $m_Q >> \Lambda_{QCD}$
  $m_c \sim 1.5$ GeV, $m_b \sim 4.5$ GeV

- Heavy quarkonium vs open bottom hadrons: B_c taking a two-fold role



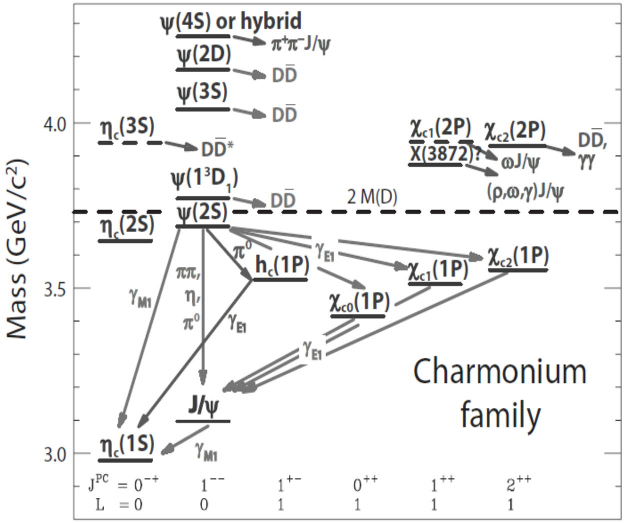
Non-relativistic potential model & spectroscopy

- Heavy quarkonium bound states below open DD, BB, DB threshold

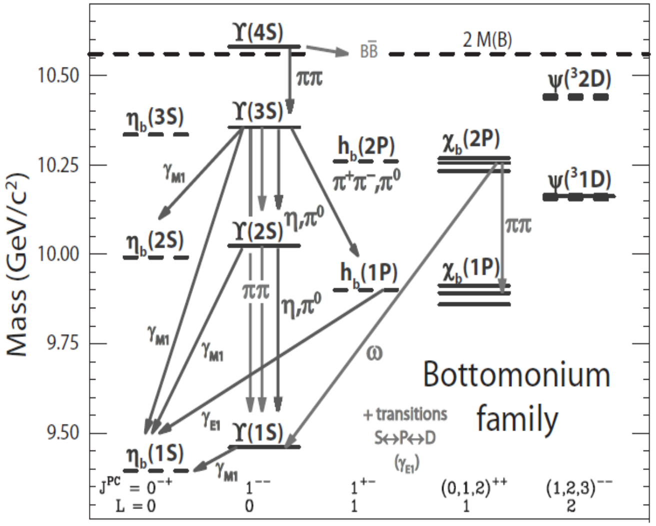
$$[2m_Q - \frac{\nabla^2}{m_Q} + V(r)]\psi_i(r) = M_i\psi_i(r)$$

- Cornell + spin-dependent potential $V(r) = -\frac{\kappa}{r} + \frac{r}{a^2}$ $V_{SS}(r) = \frac{\sigma_Q \cdot \sigma_{\bar{Q}}}{6m_Q^2}\nabla^2 V_V(r)$ $V_{LS}(r) = \frac{L \cdot S}{2m_Q^2 r}\left(3\frac{dV_V}{dr} - \frac{dV_S}{dr}\right)$

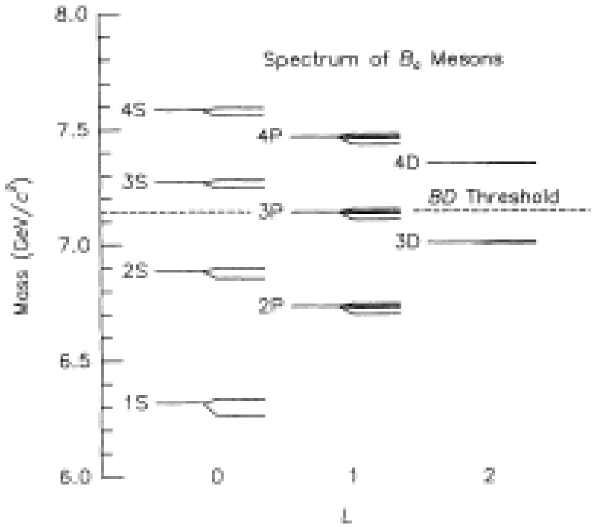
Eichten et al., RMP '05   Eichten & Quigg., '94 & '19



Charmonium



Bottomonium

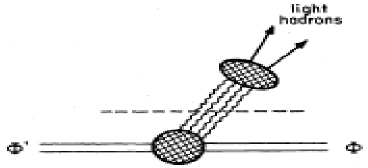


B_c mesons

14 states below DB threshold

Decay widths of B_c's below DB threshold

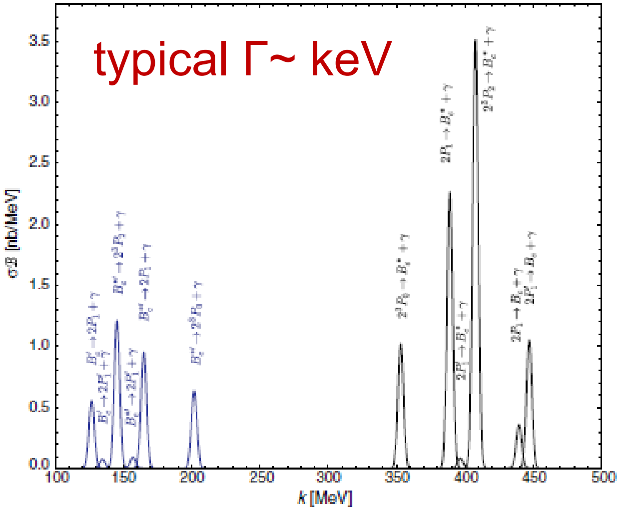
- Open charm-bottom → annihilation into gluons forbidden (vs hidden c/b quarkonium)
- Radiative decay & hadronic cascades
  - EM E1 transition $$\Gamma_{E1}(i \to f + \gamma) = \frac{4\alpha \langle e_Q \rangle^2}{27} k^3 (2J_f + 1) |\langle f | r | i \rangle|^2 \mathcal{S}_{if}$$
  - EM M1 transition $$\Gamma_{M1}(i \to f + \gamma) = \frac{16\alpha}{3} \mu^2 k^3 (2J_f + 1) |\langle f | j_0(kr/2) | i \rangle|^2$$
  - Color E1-E1 transition



Eichten & Quigg., '94 & '19

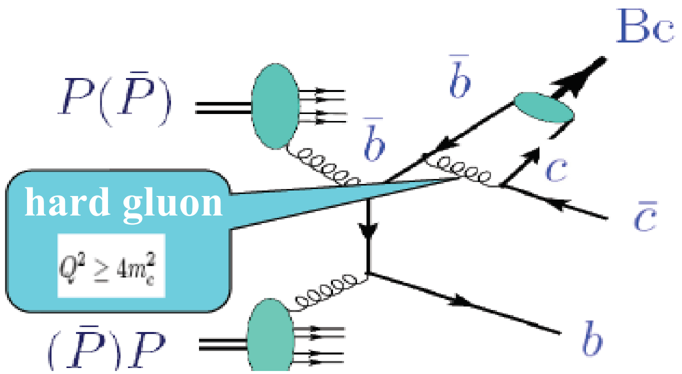
➔ All B_c's below DB threshold end up in the pseudoscalar ground state $B_c(1^1S_0)$ 100%!

Decay mode	k_γ (keV)	Branching fraction (%)
	1^1S_0 (6275): Weak decays	
	1^3S_1 (6329): $\Gamma = 0.144$ keV	
$1^1S_0 + \gamma$	54	100
	2^3P_0 (6692): $\Gamma = 53.1$ keV	
1^3S_1 (6329)	354	100
	2^1S_0 (6866): $\Gamma = 73.1$ keV	
$1^1S_0 + \pi\pi$		81.1
$2P_1'$ (6738)	126	16.5
$2P_1$ (6730)	134	2.24



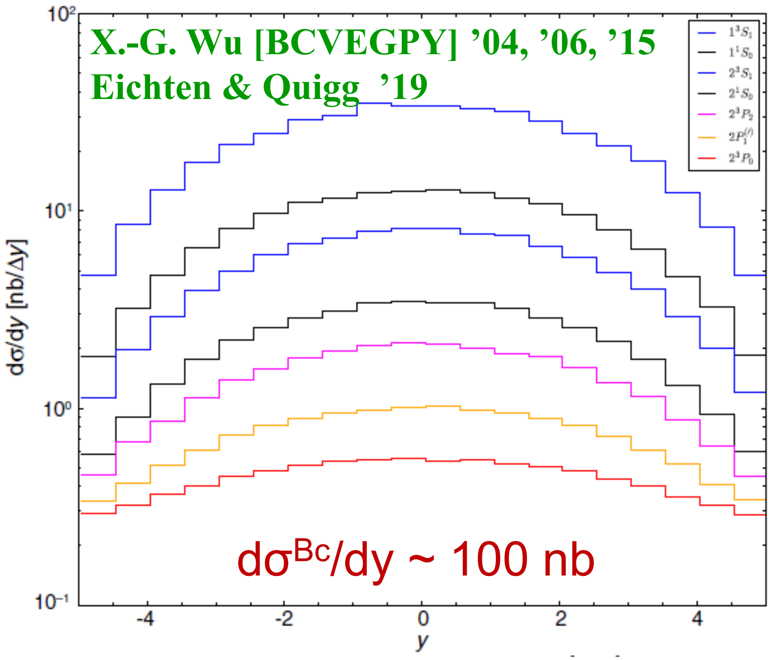
Production of B_c in pp collisions

- Gluon-gluon fusion: g + g → B_c + c + bbar $O(\alpha_s^4)$



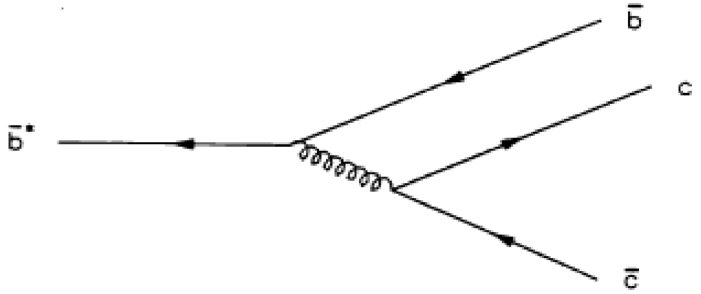
$$d\sigma = \sum_{ij} \int dx_1 \int dx_2 F^i_{H_1(P_1)}(x_1, \mu_F^2) \times F^j_{H_2(P_2)}(x_2, \mu_F^2) d\hat{\sigma}_{ij \to B_c b \bar{c}}(P_1, P_2, x_1, x_2, \mu_F^2)$$

➔ Entailing production of two heavy quark pairs in a single event: very rare & small rate!

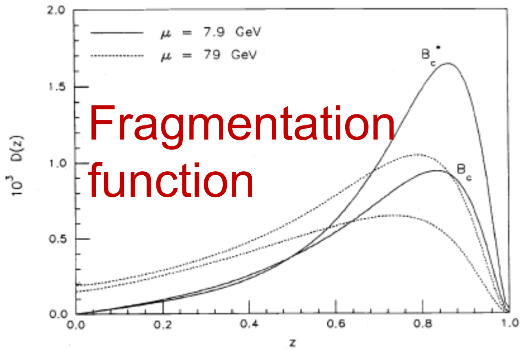


$d\sigma^{J/\psi}/dy \sim 10\ \mu b$
$d\sigma^{\Upsilon(1S)}/dy \sim 300$ nb
all @13 TeV

- Equivalent to b-quark fragmentation : b→B_c >> c→B_c



Braaten et al., '93



$$D_{\bar{b}\to B_c}(z, m_b + 2m_c) = \frac{2\alpha_s(2m_c)^2|R(0)|^2}{81\pi m_c^3} \frac{rz(1-z)^2}{[1-(1-r)z]^6} \Big(6 - 18(1-2r)z + (21 - 74r + 68r^2)z^2 - 2(1-r)(6 - 19r + 18r^2)z^3 + 3(1-r)^2(1 - 2r + 2r^2)z^4 \Big)$$

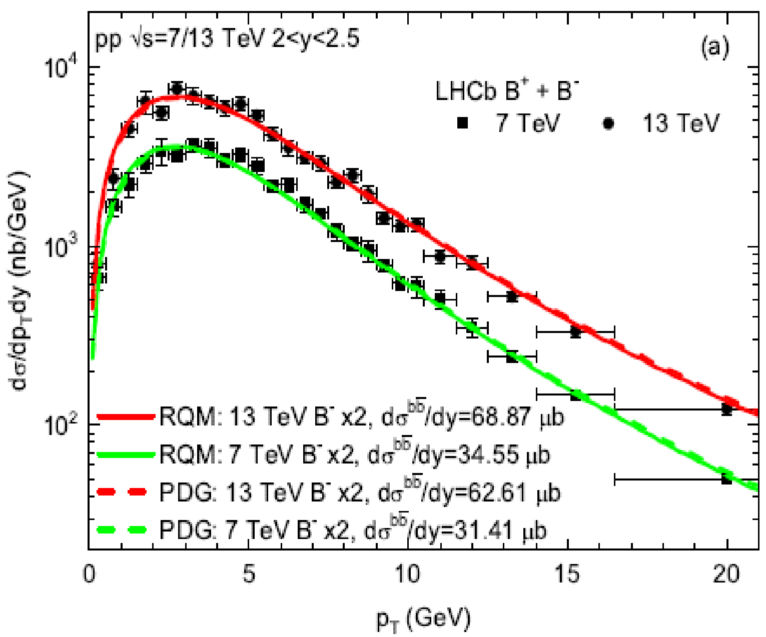
B_c^- vs B^- fragmentation fractions in pp @ LHC

- b-quark conservation through hadronization/fragmentation

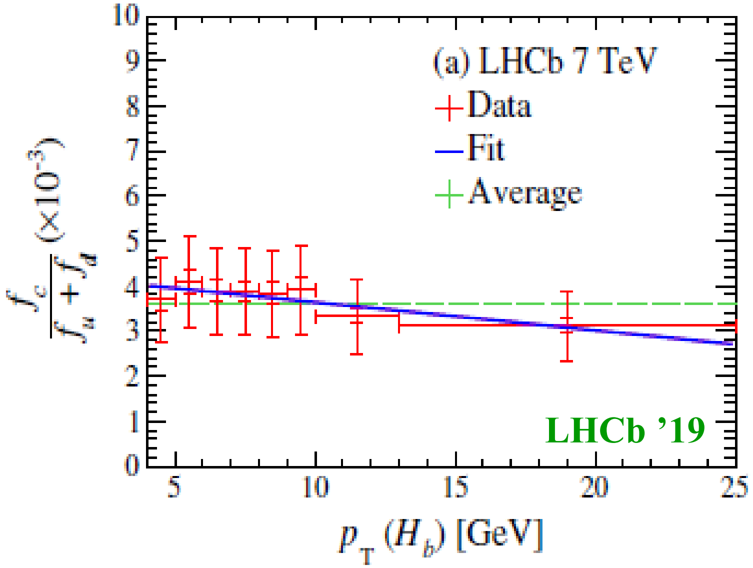
$$f_u + f_d + f_s + f_{b-baryons} + \underbrace{f_c + f_{bottomonium}}_{\text{tiny}} = 1$$

f_α	B^-	$\bar{B}^0$	$\bar{B}_s^0$	Λ_b^0	$\Xi_b^{0,-}$
PDG(170)	0.3697	0.3695	0.1073	0.1157	0.03698
RQM(170)	0.3391	0.3389	0.09152	0.1737	0.05503

MH & Rapp '23



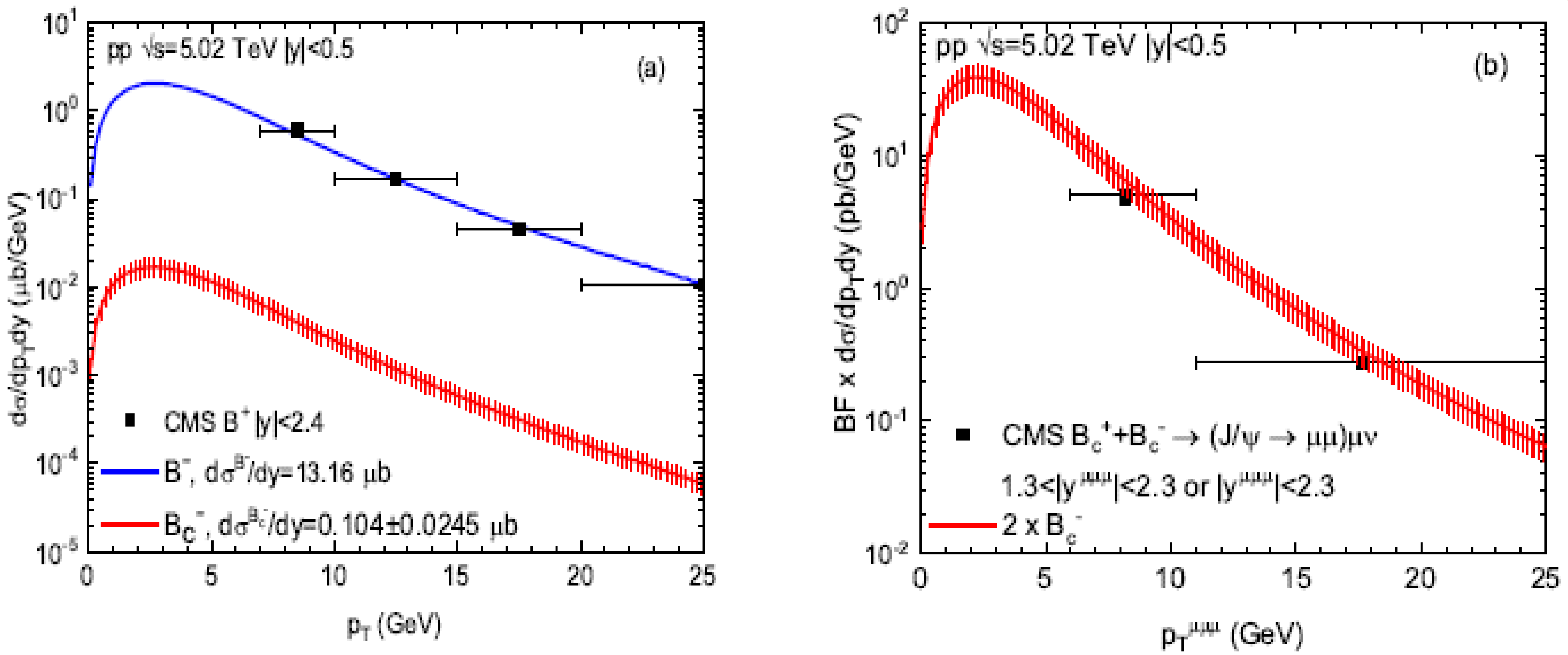
- Production fractions: B_c VS B



- Major uncertainty from Br(B_c→J/ψ+μ+ν)=(1.95±0.46)%

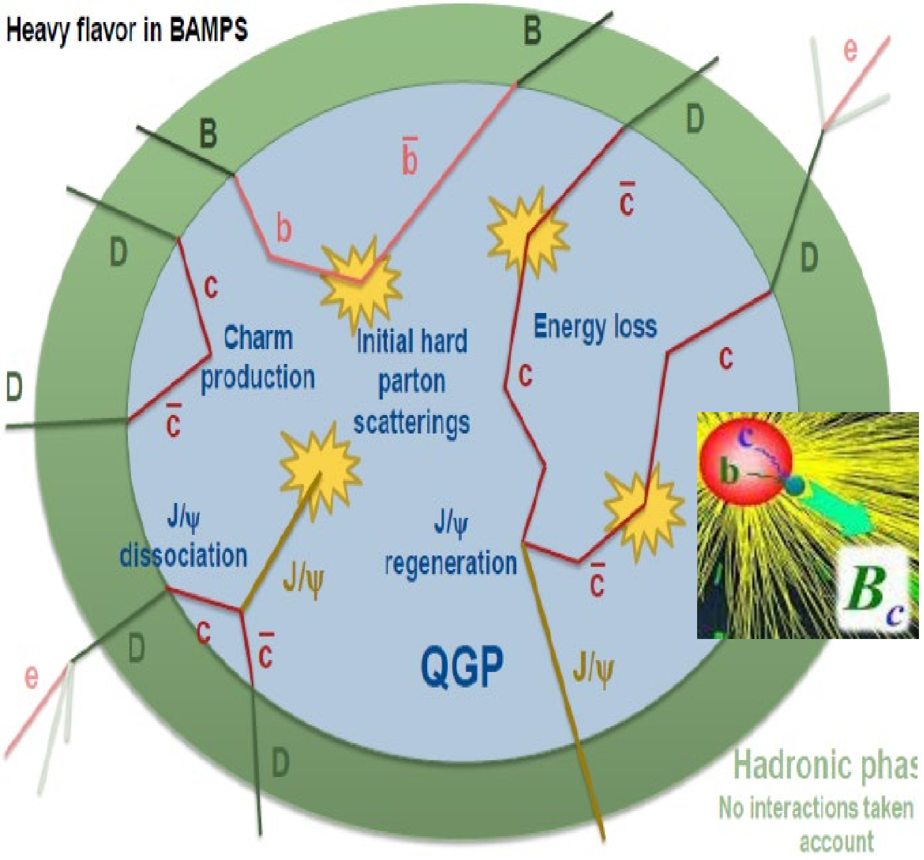
- $B_c^-/(B^- + B^0\text{bar})$ $\quad \dfrac{f_c}{f_u + f_d} = (3.63 \pm 0.08 \pm 0.12 \pm 0.86) \times 10^{-3}$

B_c^- vs B^- cross section in 5 TeV pp @ LHC



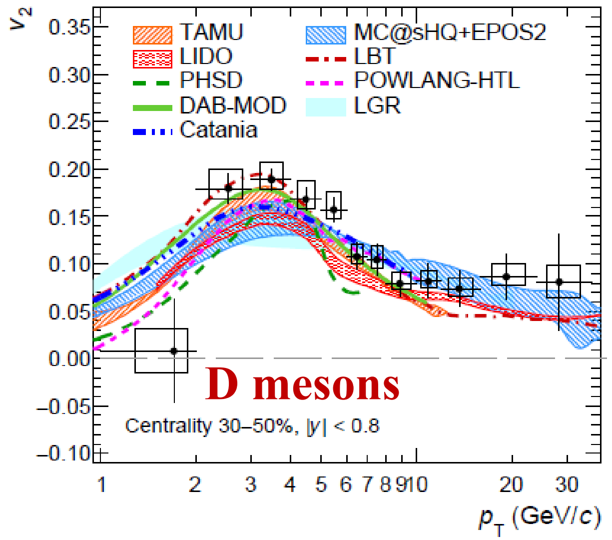
- Production ratio insensitive to energy ➔ $d\sigma(B_c^-) = d\sigma(B^-) * f_c/f_u$ @ 5TeV ➔ baseline for Pb-Pb
- $d\sigma(B_c^-)/dy = 0.104 \pm 0.0245$ μb & $f_c = 0.00258 \pm 0.00062$ @ 5 TeV
- CMS: BF=Br(B_c→J/ψ+μ+v)*Br(J/ψ→μ+μ) & $p_T(\mu\mu\mu)=0.855 * p_T(B_c)$

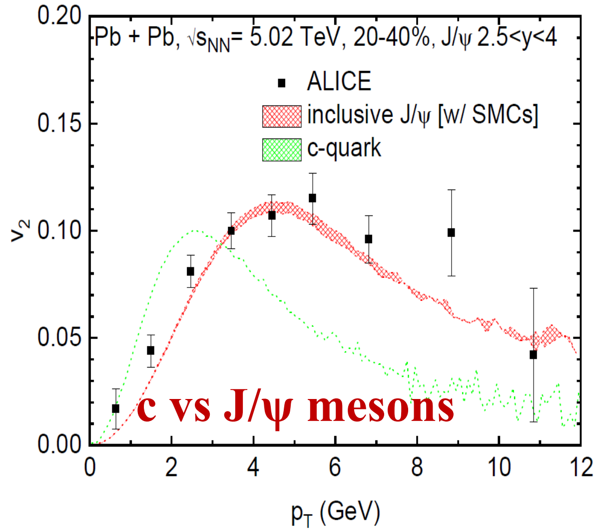
B_c production in Pb-Pb collisions @ LHC



- dN^{ccbar}/dy~20 & dN^{bbbar}/dy~1 for central collisions

- c & b quarks diffusing & thermalizing in QGP via rescatterings
  → especially low p_T c quarks near-fully thermalized





- Abundance + softening facilitating recombination b+cbar→B_c

  Quarkonium transport: Thews et al. ’00; Zhuang et al.,’13, ’22; Rapp et al. ’24

- Implemented stochastically → statistical hadronization

Statistical production of heavy hadrons in Pb-Pb

- Canonical ensemble partition function: strict conservation of c & b number

$$Z(C,B)=\lambda_Q\lambda_N\lambda_S\frac{1}{(2\pi)^2}\int_0^{2\pi}d\phi_C d\phi_B e^{i(C\phi_C+B\phi_B)}\times\exp\Big[\sum_j\gamma_s^{N_{sj}}\gamma_c^{N_{cj}}\gamma_b^{N_{bj}}e^{-i(C_j\phi_C+B_j\phi_B)}z_j\Big],$$

$$z_j=(2J_j+1)\frac{VT_H}{2\pi^2}m_j^2K_2\left(\frac{m_j}{T_H}\right)$$

T_H~170 MeV

- Heavy hadron primary yield

$$\langle N_j\rangle=\gamma_s^{N_{sj}}\gamma_c^{N_{cj}}\gamma_b^{N_{bj}}z_j\frac{Z(C-C_j,B-B_j)}{Z(C,B)}$$

chemical factor <1: canonical suppression for c and b hadrons

- Strangeness γ_s=1 but γ_c & γ_b by balance equation: c/b conservation through hadronization

$$\frac{dN_{c\bar{c}}}{dy}=\sum_{j\in oc^+}\langle N_j\rangle+\sum_{j\in hc}\langle N_j\rangle+\sum_{j\in B_c^+}\langle N_j\rangle$$

$$\frac{dN_{b\bar{b}}}{dy}=\sum_{j\in ob^+}\langle N_j\rangle+\sum_{j\in hb}\langle N_j\rangle+\sum_{j\in B_c^+}\langle N_j\rangle$$

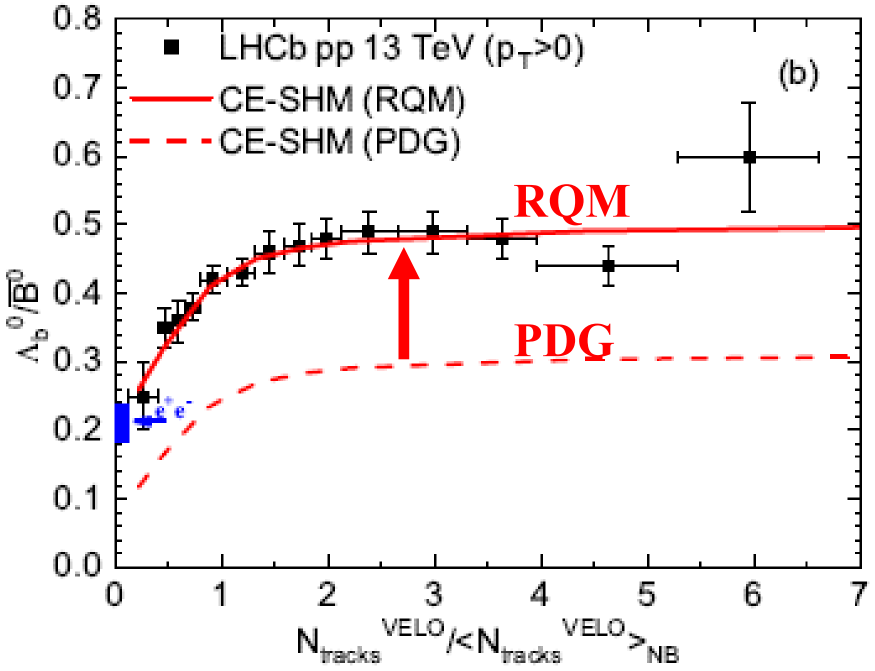
Input c/b-hadron spectrum & c/b fugacities

- PDG: 5 B, 4 B_s, 5 Λ_b, 2 Σ_b, 4 Ξ_b, 1 Ω_b

↓

RQM: 25 B, 20 B_s, 30 Λ_b, 46 Σ_b, 75 Ξ_b, 42 Ω_b

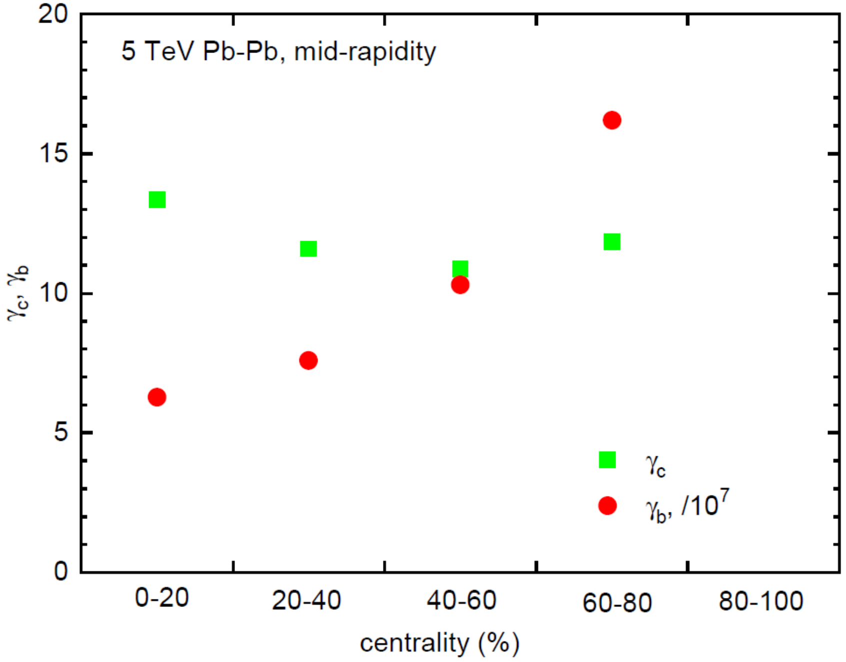
➔ "Missing" states/baryons essential for explaining Λ_b/B, Λ_c/D enhancement



MH & Rapp '23, Dai & MH '24

- γ_c & γ_b vs centrality

	0-20%	20-40%	40-60%	60-80%
$V_{\Delta y=1}(\text{fm}^3)$	4170	1849	709	200
$dN_{c\bar{c}}/dy$	17.2	6.46	2.15	0.44
$dN_{b\bar{b}}/dy$	0.74	0.272	0.0806	0.0165
γ_c	13.35	11.58	10.87	11.84
γ_b	$6.27 \cdot 10^7$	$7.59 \cdot 10^7$	$1.03 \cdot 10^8$	$1.62 \cdot 10^8$



B_c mesons yields & fractions

- Total ground-state yields $\langle N_\alpha^{tot}\rangle = \langle N_\alpha\rangle + \sum_j \langle N_j\rangle \cdot \mathcal{B}(j \to \alpha)$

dN/dy	0-20%	20-40%	40-60%	60-80%
$B^-(=\bar{B}^0)$	0.23234	0.085594	0.025373	0.0051834
$\bar{B}_s^0$	0.097318	0.035851	0.010628	0.0021711
Λ_b^0	0.11664	0.042969	0.012738	0.0026021
$\Xi_b^{0,-}$	0.061520	0.022664	0.0067183	0.0013725
Ω_b^-	0.0031317	0.0011537	0.00034199	0.000069866
B_c^-	0.010001	0.0031222	0.00080467	0.00012052
B_c^-/B^-	0.043056	0.036489	0.031724	0.02326
$f_c = B_c^-/b\bar{b}$	0.013276	0.011275	0.009817	0.00722

$\Lambda_b/B \sim 0.5$ reproducing grand-canonical SHM results MH & Rapp '23

- B_c placed as a member of open b-hadron family, instead of quarkonium
  ➔ predictions for its production fraction from b-conservation

- $B_c^-/B^- \sim 0.043$ vs 0.0079 (pp), $f_c=B_c^-$/bbbar ~ 0.013 vs 0.00258 (pp)
  ➔ ~ 5x enhancement: statistical recombination in deconfined QGP!

- Central➔peripheral: f_c↘ from canonical suppression due to strict c-conservation!

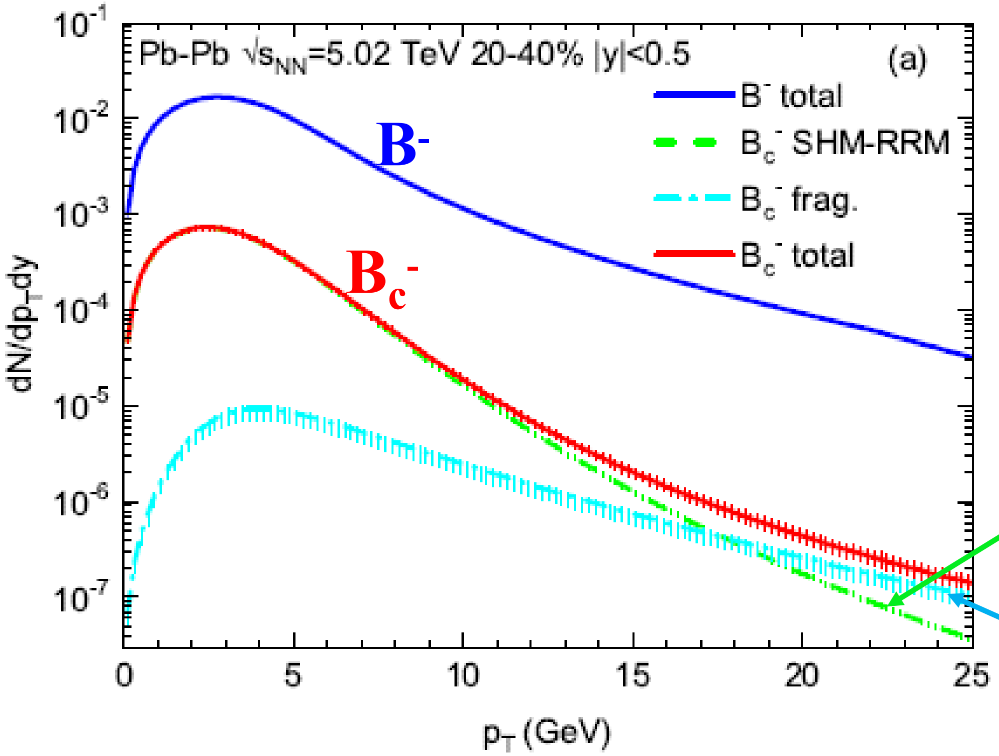
B_c mesons p_T-differential yield

- Converting B_c yield into p_T spectrum via Resonance Recombination Model

$$f_{B_c}(\vec{x},\vec{p}) = C_{B_c} \frac{E_{B_c}(\vec{p})}{m_{B_c}\Gamma_{B_c}} \int \frac{d^3\vec{p}_1 d^3\vec{p}_2}{(2\pi)^3} f_b(\vec{x},\vec{p}_1) f_{\bar{c}}(\vec{x},\vec{p}_2) \times \sigma_{B_c}(s) v_{\mathrm{rel}}(\vec{p}_1,\vec{p}_2) \delta^3(\vec{p}-\vec{p}_1-\vec{p}_2) \quad (8)$$

Normalized to statistical hadronization yield

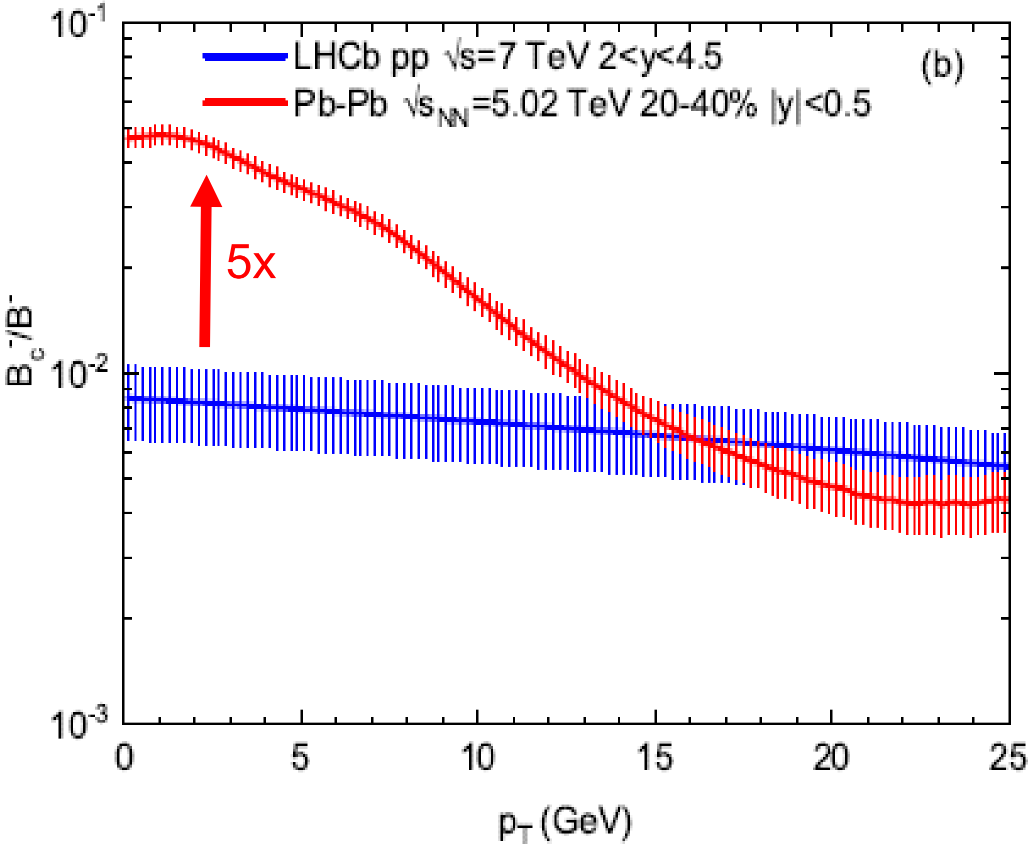
b/c distributions from Langevin diffusion simulation constrained by D/B data

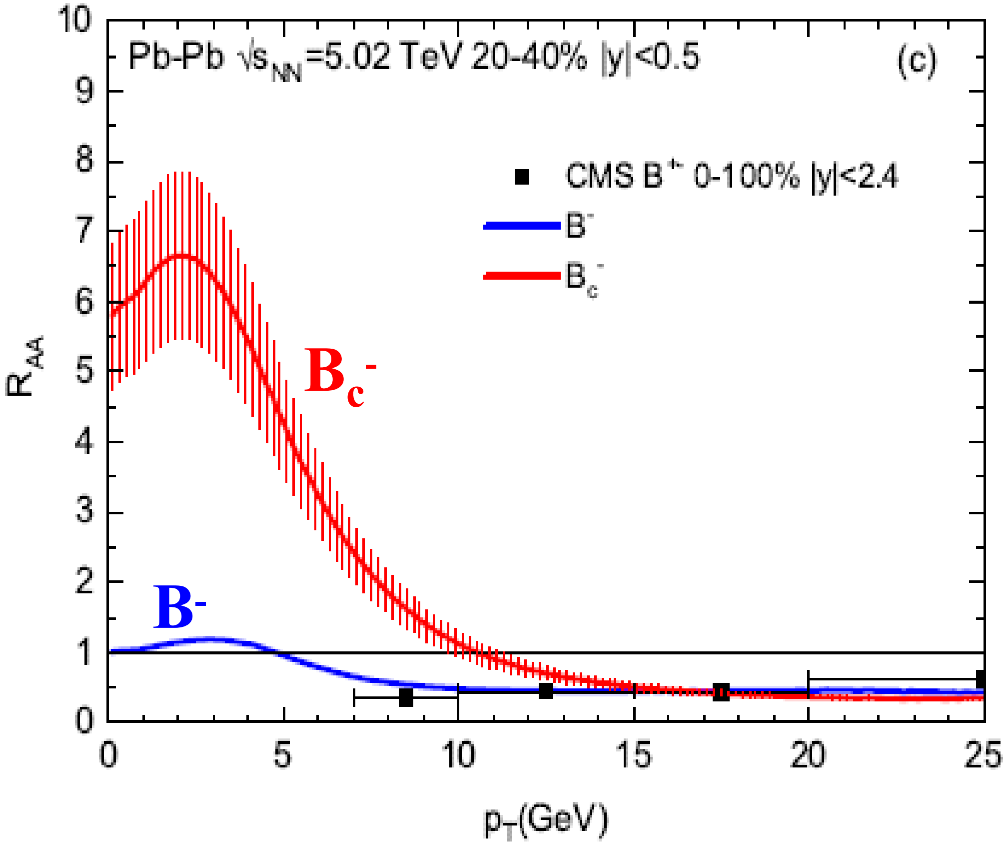


resonance recombination

quenched b-quark → fragmentation

B_c vs B: ratio & nuclear modification factor

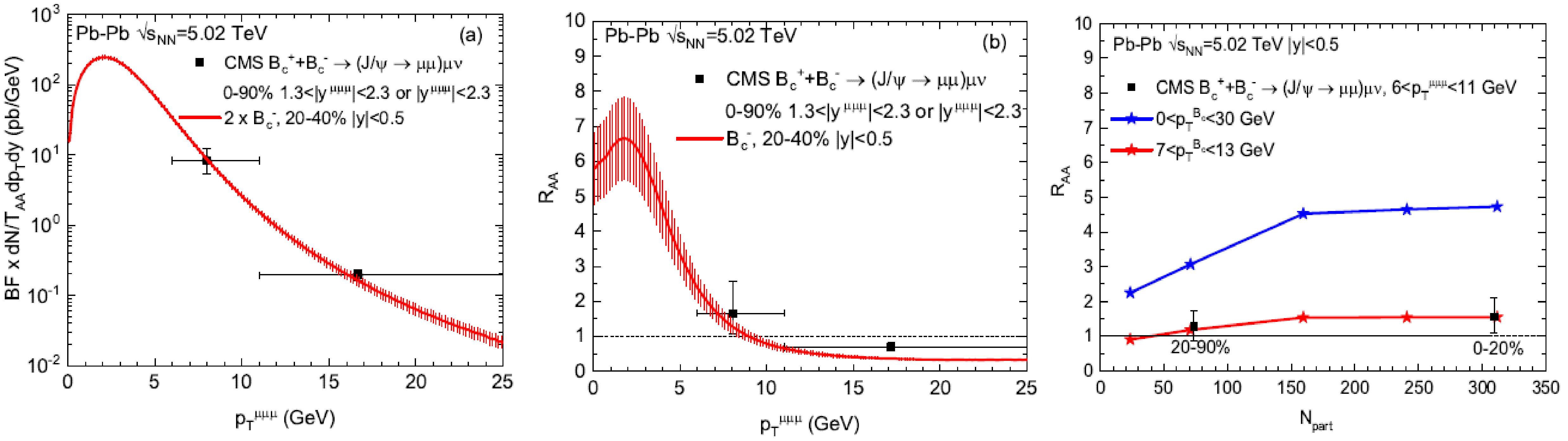




- B_c^-/B^- : ~ 5x enhancement at low p_T in Pb-Pb vs pp, but converging at high p_T
- $R_{AA}(B_c^-)$ ~ 5-6 at low p_T vs $R_{AA}(B^-)$ ~1 but converging at high p_T

Confronting CMS data

- CMS PRL128(2022)252301: BF=Br(B_c→J/ψ+μ+v)*Br(J/ψ→μ+μ) & p_T(μμμ)=0.855*p_T(B_c)



- Normalized p_T differential yield well reproduced
- ~50% enhancement (R_{AA}~1.5) in the lower p_T bin well captured
- Enhancement diminishing in peripheral: canonical suppression of statistical production

Summary & outlook

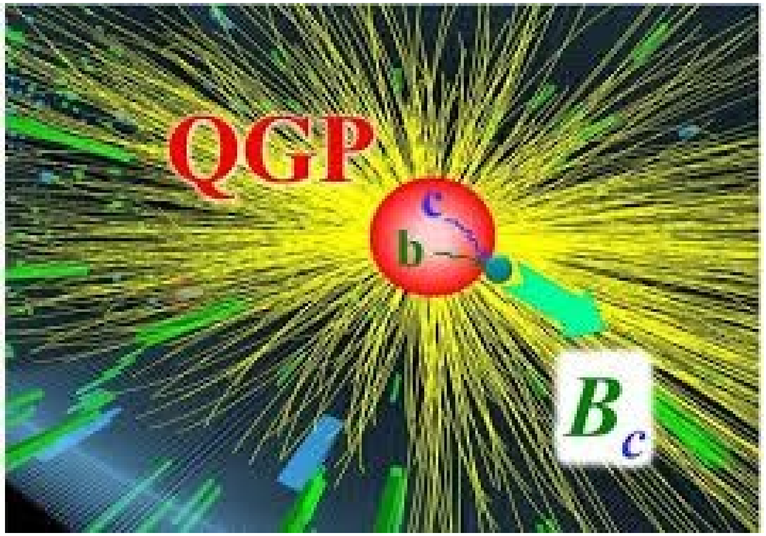
- Recombination of abundant & near-thermalized c & b quarks
  ➔ statistical production of B_c mesons

- B_c treated as a member of the family of open b hadrons
  ➔ 5x enhancement of f_c & B_c^-/B^- & R_{AA} predicted at low p_T

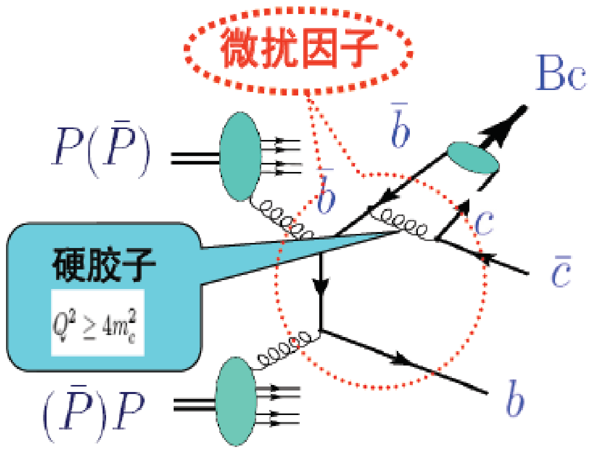
- Awaiting exp data pushed down to p_T~0
  ➔ to confirm statistical recombination production of B_c mesons

- Measurements & model calculations of v_2

➔ strong evidence of formation of a deconfined QCD medium -- QGP!



Back-up: B_c production at Z-factory VS in pp



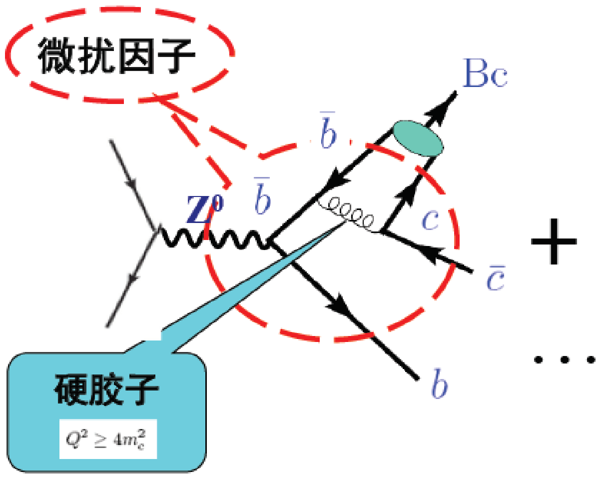
Gluon-gluon fusion mechanism dominant

Subprocess: $gg \to B_c + c + \bar{b}$

36 Feynman diagrams for complete calculations

The information about the accompany quark-jets interests experimentalists

- This is t-channel gg
- Can also be s-channel gg/qqbar annihilation into b-bbar ?
- bbar-c can be in color-octet first and then transition into singlet Bc meson via gluon radiation, like NRQCD ?



The key point is the hard gluon & it can be QCD factorized as indicated by the figure.

PRD**46**, (1992) 3845; PLB**284**, (1992) 127; PRD93 (2016) 034019