Open heavy flavor and quarkonium production in EPOS4

Jiaxing Zhao (SUBATECH)

jzhao@subatech.in2p3.fr

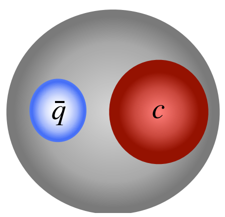
In collaboration with Jörg Aichelin, Pol Bernard Gossiaux, Klaus Werner

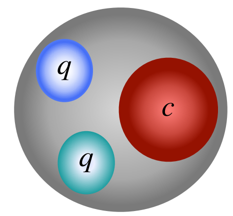
29/05/2024

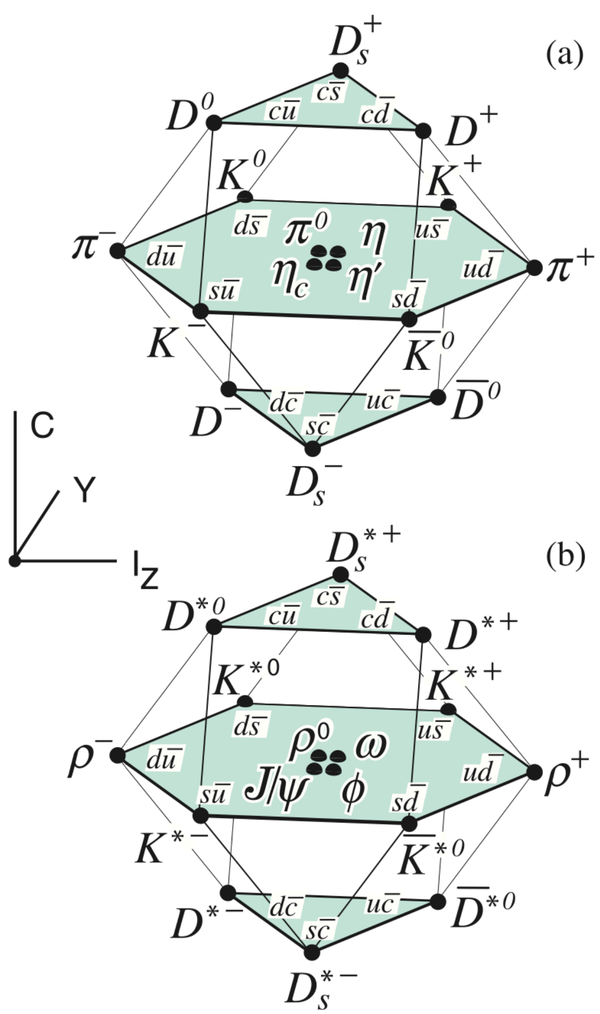
Open heavy flavor

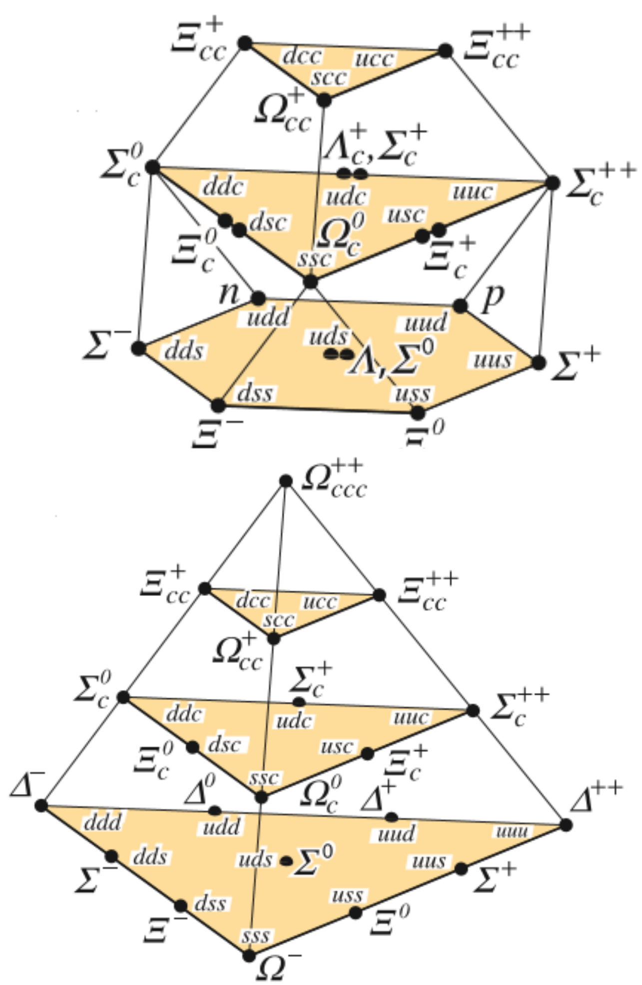
$$D^0, D^+, D_s^+, \Lambda_c, \Xi_c, \Omega_c, \ldots$$

$$B^0, B^-, B_s^0, \Lambda_b, \Xi_b, \Omega_b, \ldots$$







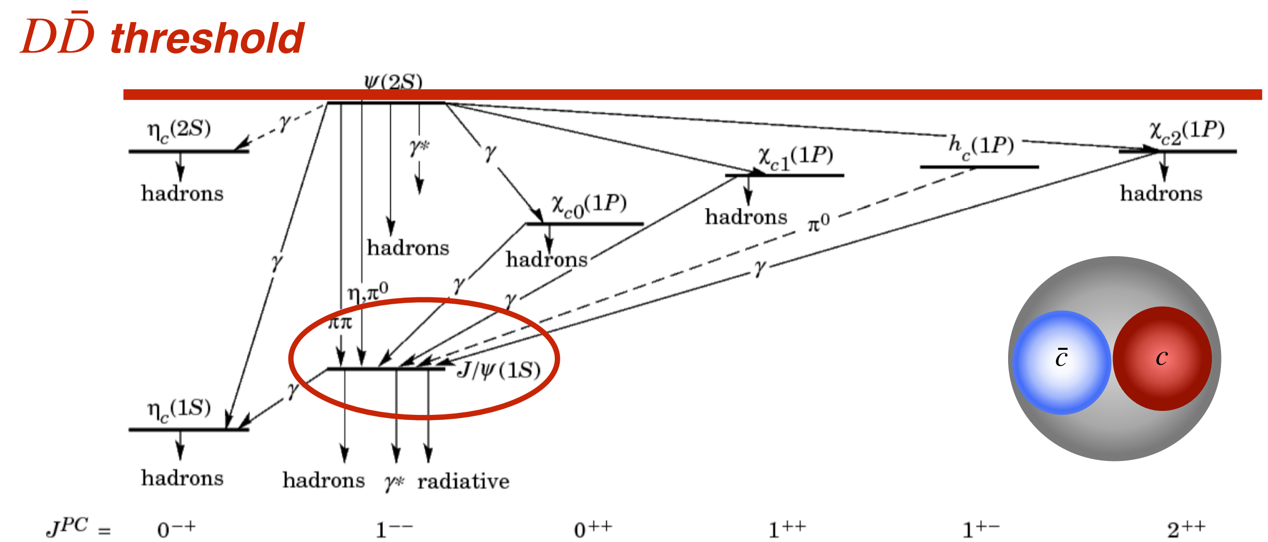


Meson

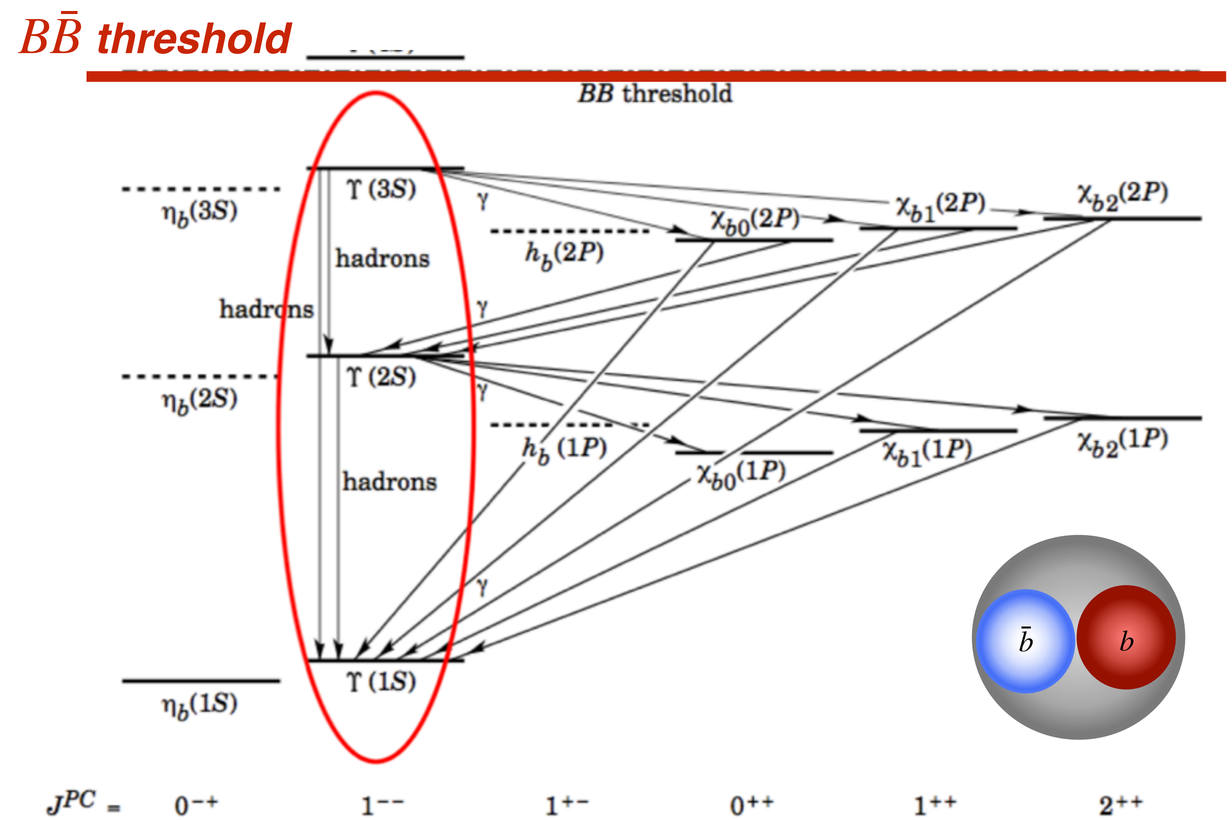
Baryon

SU(4) quark model

Quarkonium



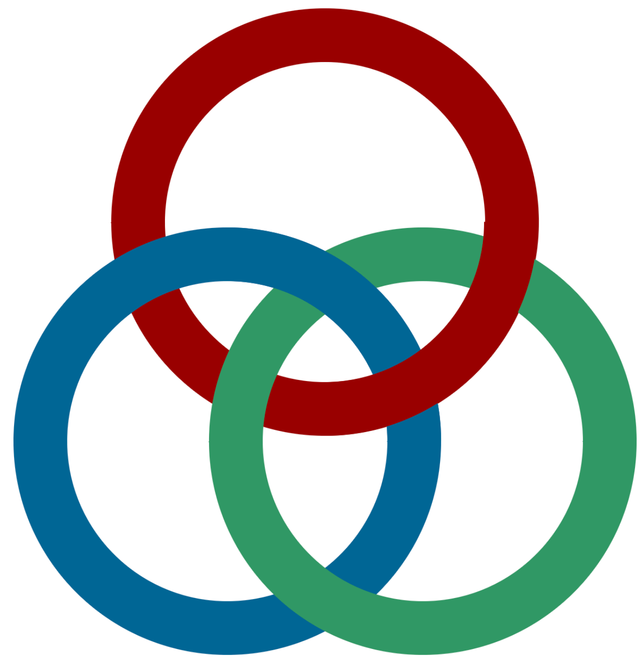
Charmonium



Bottomonium

Bulid a unified framework

Light hadrons



Thermal medium properties:
EOS, lifetime,temperature,
volicity, shear viscosity…

Thermal medium properties:
EOS, lifetime,temperature,
volicity, shear viscosity…

Open heavy flavor

Catania model
PHSD model
Duke model
LBT model
TAMU model
Tsinghua model
Nantes model (previous)
Torino model
…

Quarkonium

TAMU model
Tsinghua model
Comover model
Many new progress based o
open-quantum system:
Munich-KSU model
Nantes model
Osaka model
PHSD-Nantes model
…

Heavy quark energy loss
Quark number conservation
Correlations
…

EPOS4: Give us a chance to combine light with heavy, open heavy flavor with quarkonium, from small to large collision systems!

Outline

- **A brief Introduction to EPOS4**
- **Open heavy flavor production in EPOS4**
- **Quarkonium production in EPOS4**

EPOS4

EPOS4: A Monte Carlo tool for simulating high-energy scatterings

VENUS(1990)—>NEXUS(2000)—> EPOS1(2002)—>EPOS2(2010)—>EPOS3(2013)—>EPOS4(2020)

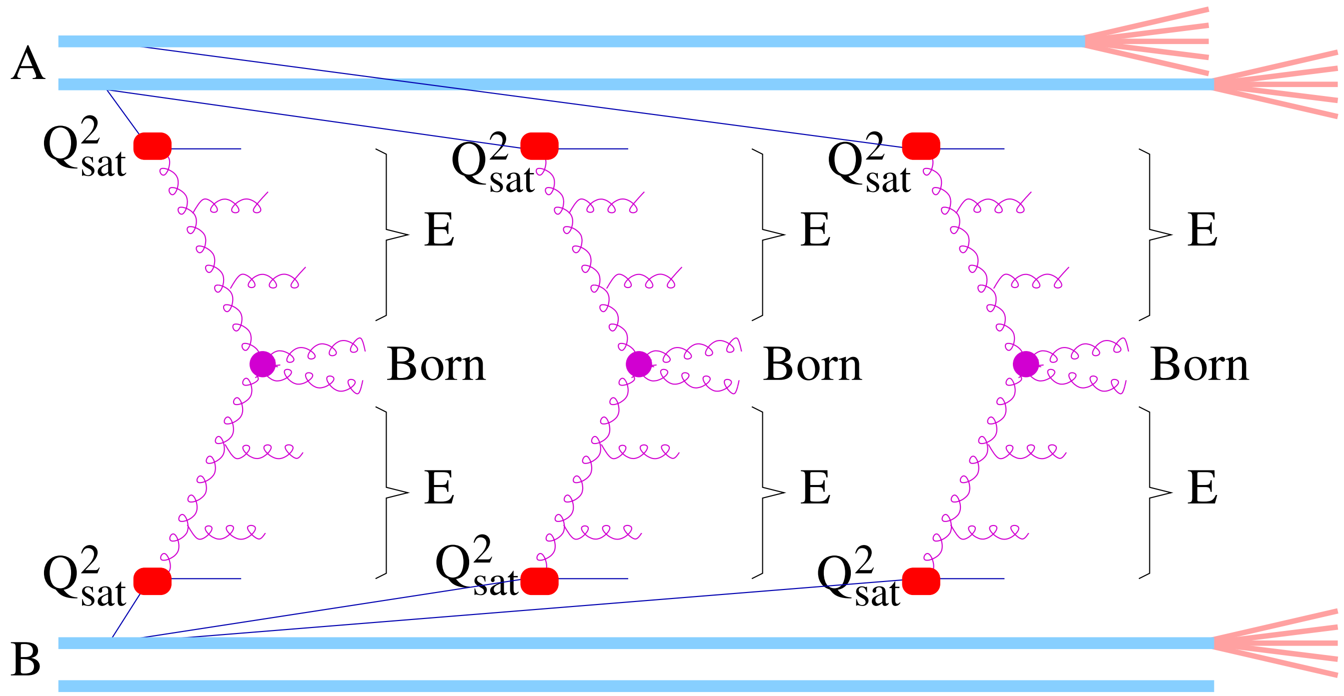
https://klaus.pages.in2p3.fr/epos4/

*An abbreviatation of **E**nergy conserving quantum mechanical multiple scattering approach, based on **P**arton (parton ladders), **O**ff-shell remnants, and **S**aturation of parton ladders.*

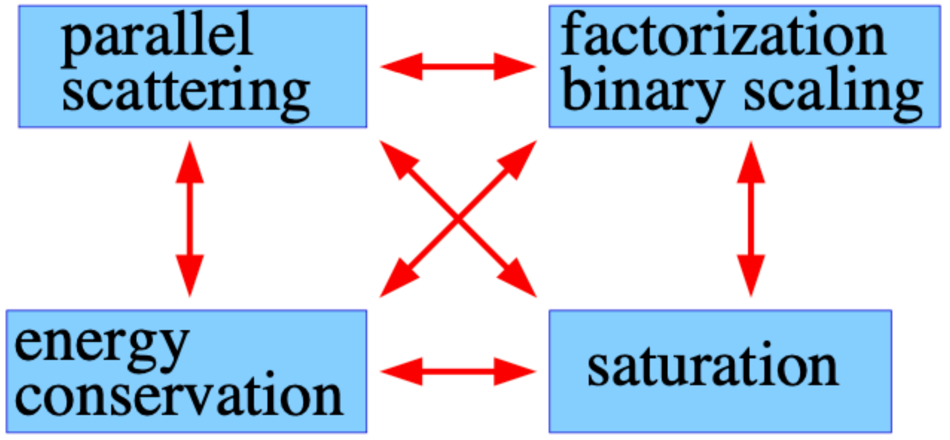
K. Werner. PRC 108 (2023) 6, 064903

K. Werner, B. Guiot, PRC 108 (2023) 3, 034904

K. Werner, PRC 109 (2024) 1, 014910



e.g. three parallel scatterings

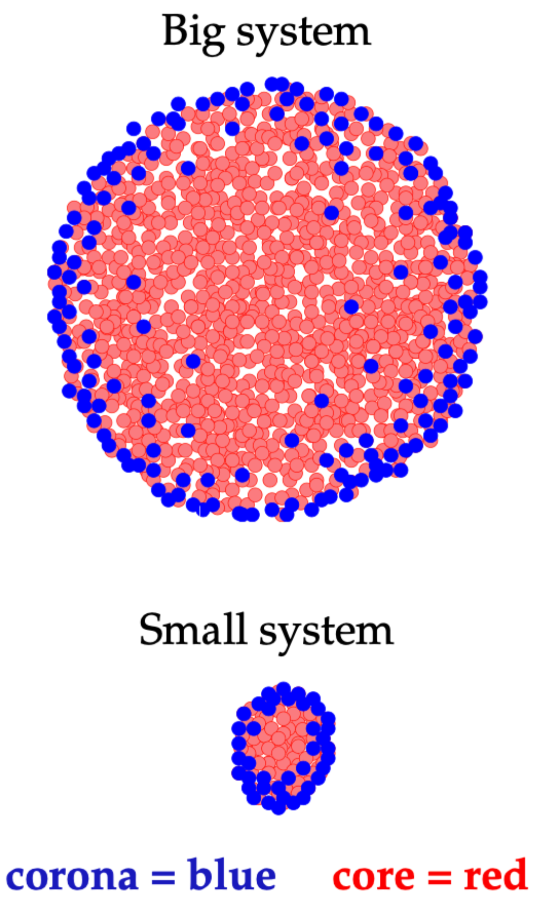


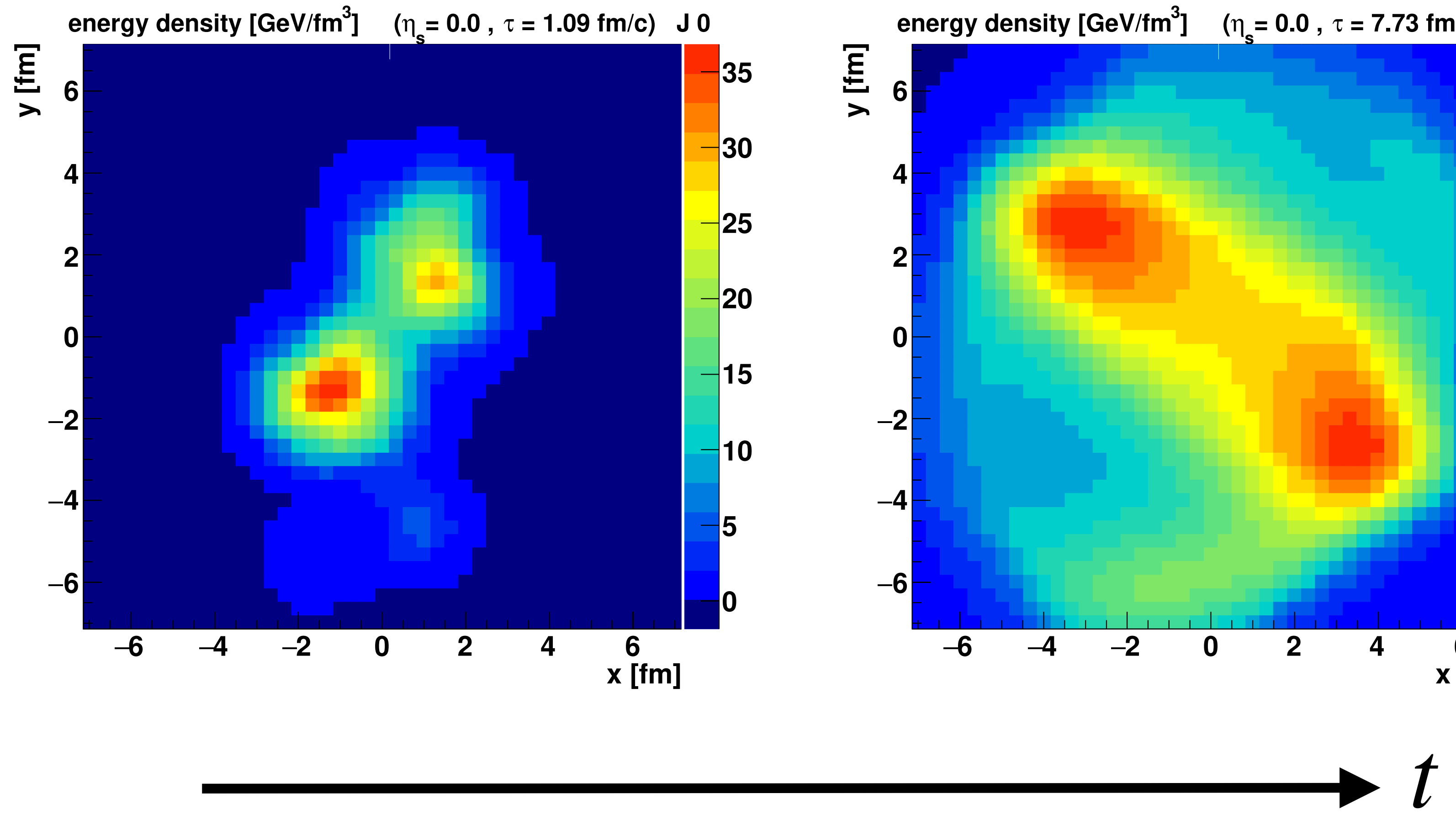
S-matrix theory (to deal with parallel scatterings happens in high energy collisions)

For each one we have a parton evolution according to some evolution function, such as DGLAP .

Consistently accommodate these four crucial concepts is realized in the EPOS4!

EPOS4: core-corona picture





- ➡ *If the energy loss is bigger than the energy of the prehadron, it is considered to be a "core"*
- ➡ *If the energy loss is smaller than the energy, the prehadron escapes, it is called "corona"*

Core: hydrodynamics (vHLLE); Corona: hadronic phase (UrQMD)

The energy density is larger than the critical energy density ϵ_0
—> deconfined QCD matter!

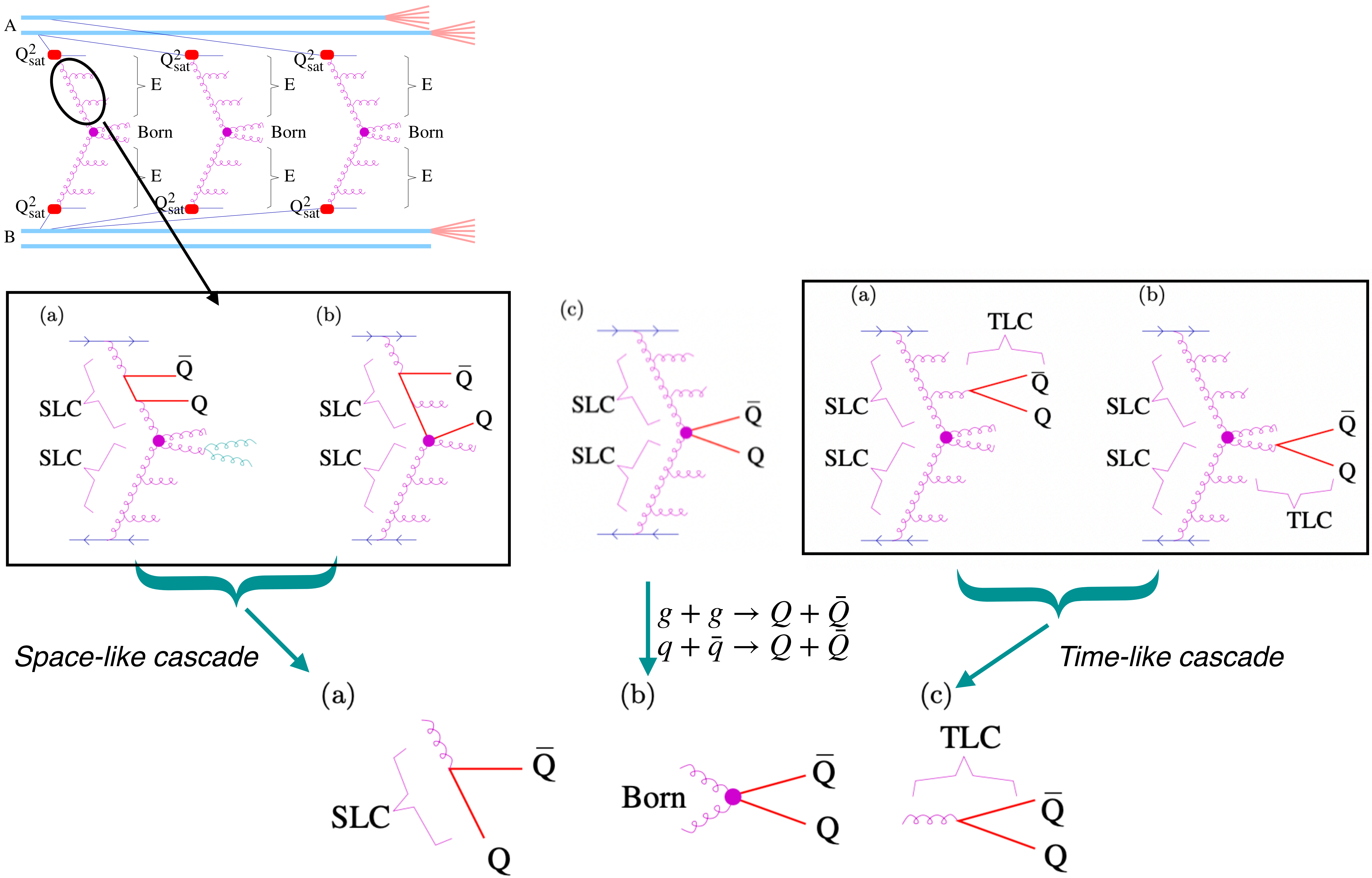
Light hadrons have been described well from pp to AA!

Outline

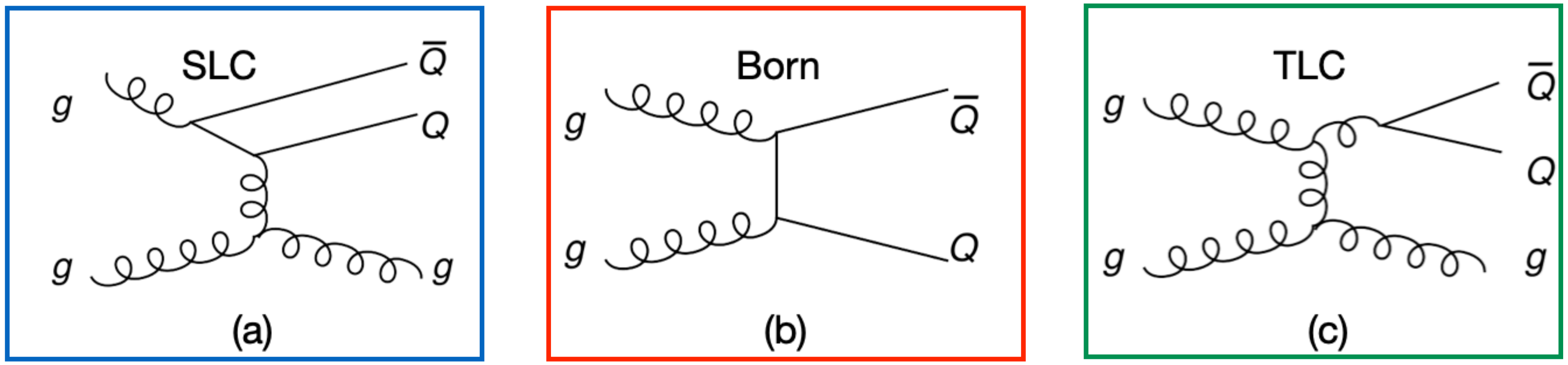
- A brief Introduction to EPOS4
- **Open heavy flavor production in EPOS4**
- Quarkonium production in EPOS4

EPOS4: heavy quark production

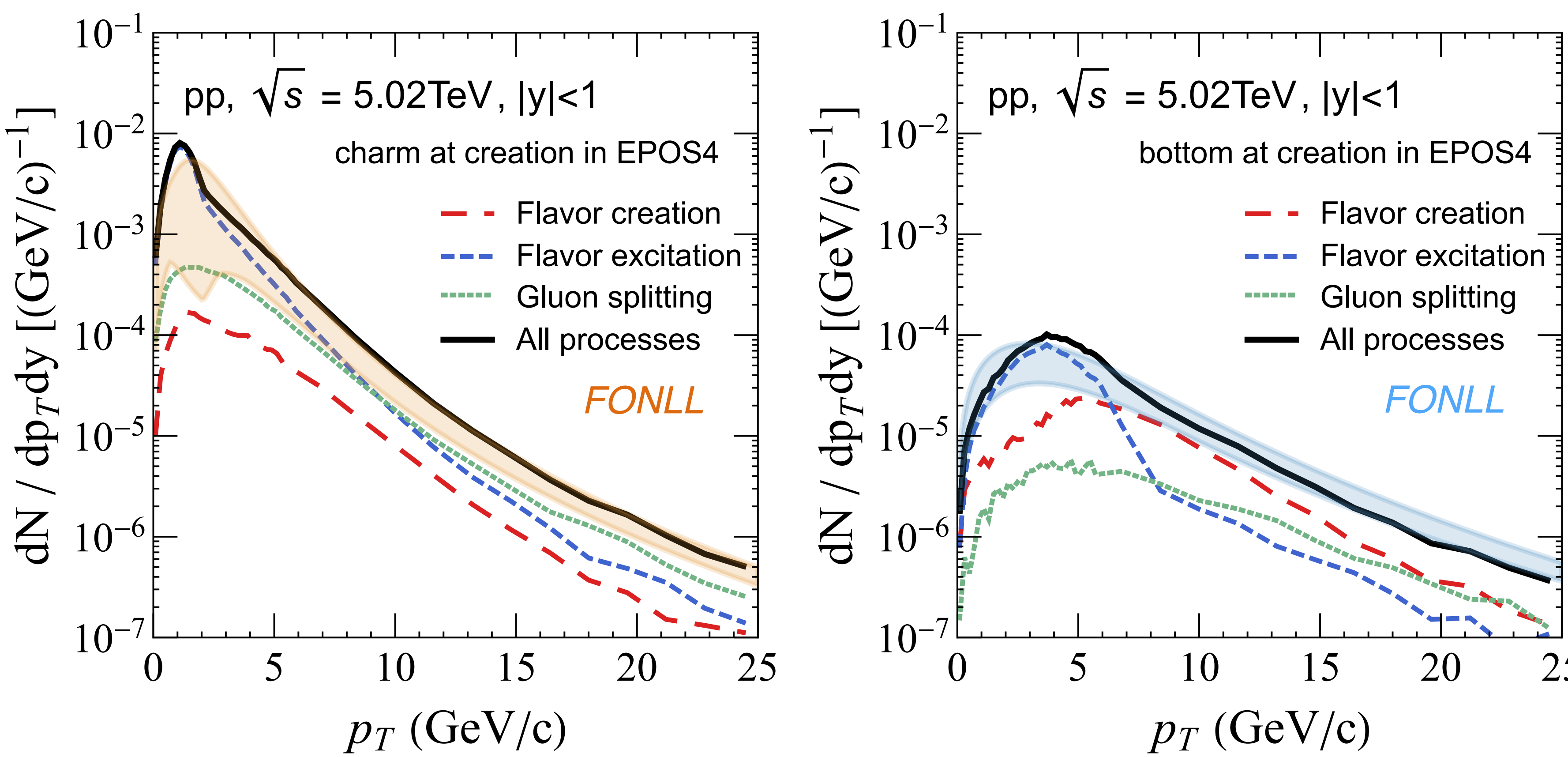
Heavy quarks are produced initially via:



EPOS4: heavy quark production



Flavor excitation *Flavor creation* *Gluon splitting*



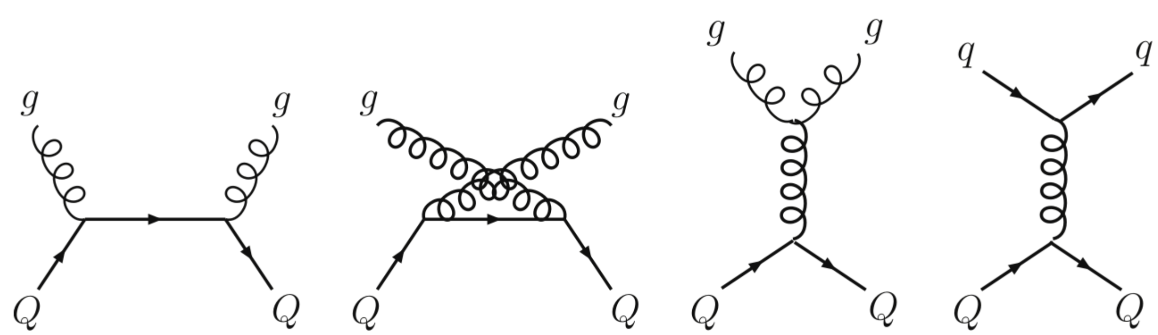
Fixed order next to leading log

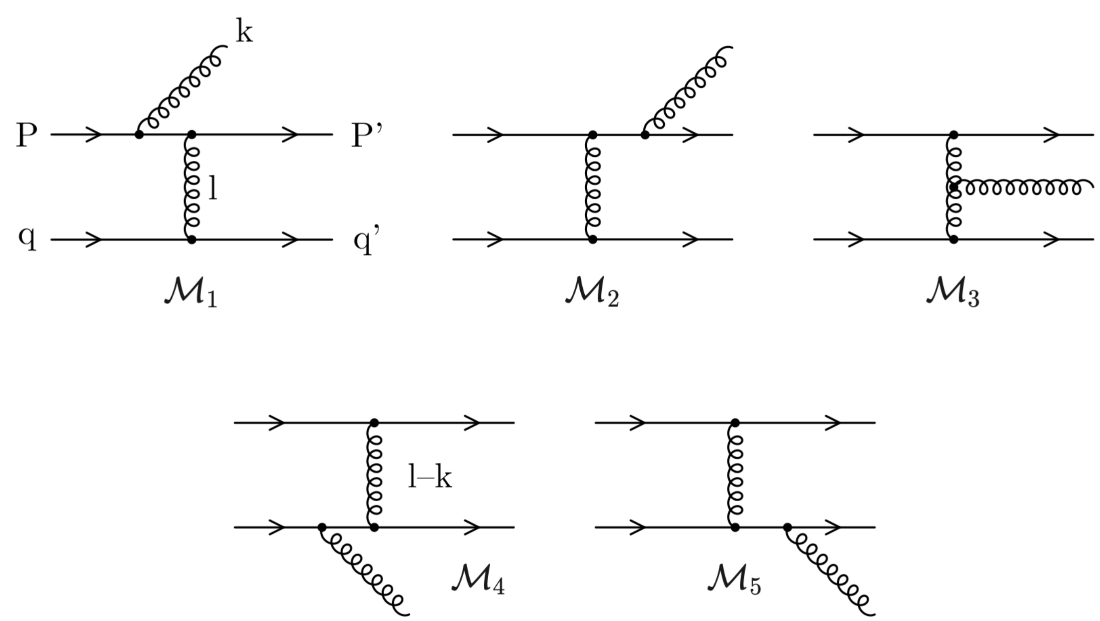
Flavor excitation dominates at low p_T while gluon splitting becomes important at high p_T.

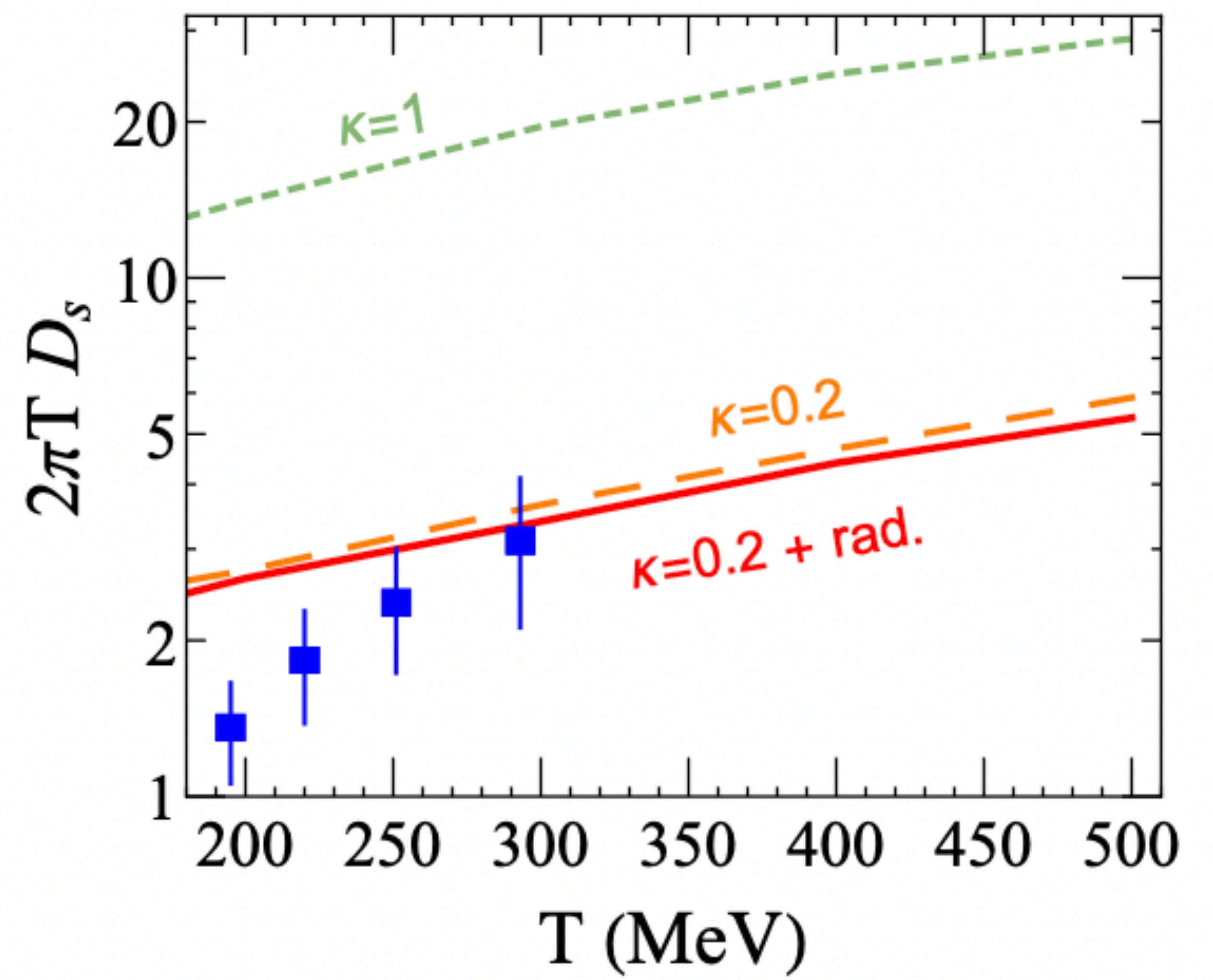
EPOS4: heavy quark energy loss

Heavy quark is treated as a Brownian particle and its evolution is described by the Boltzmann equation

Both collisional and radiative energy loss are included







P.B. Gossiaux. J. Aichelin. Phys.Rev.C 78 (2008) 014904.

J. Aichelin, P. B. Gossiaux, and T. Gousset, Phys. Rev. D 89, 074018 (2014)

***JZ,** J.Aichelin, P.B. Gossiaux, V. Ozvenchuk, K.Werner, arXiv:2401.17096*

EPOS4HQ: heavy quark hadronization

When the local energy density is lower than the critical value (T~165MeV)

Heavy quarks hadronize into heavy flavor hadrons!

- ***Fragmentation***

  Peterson Fragmentation, HQET-based Fragmentation, String Fragmentation,…

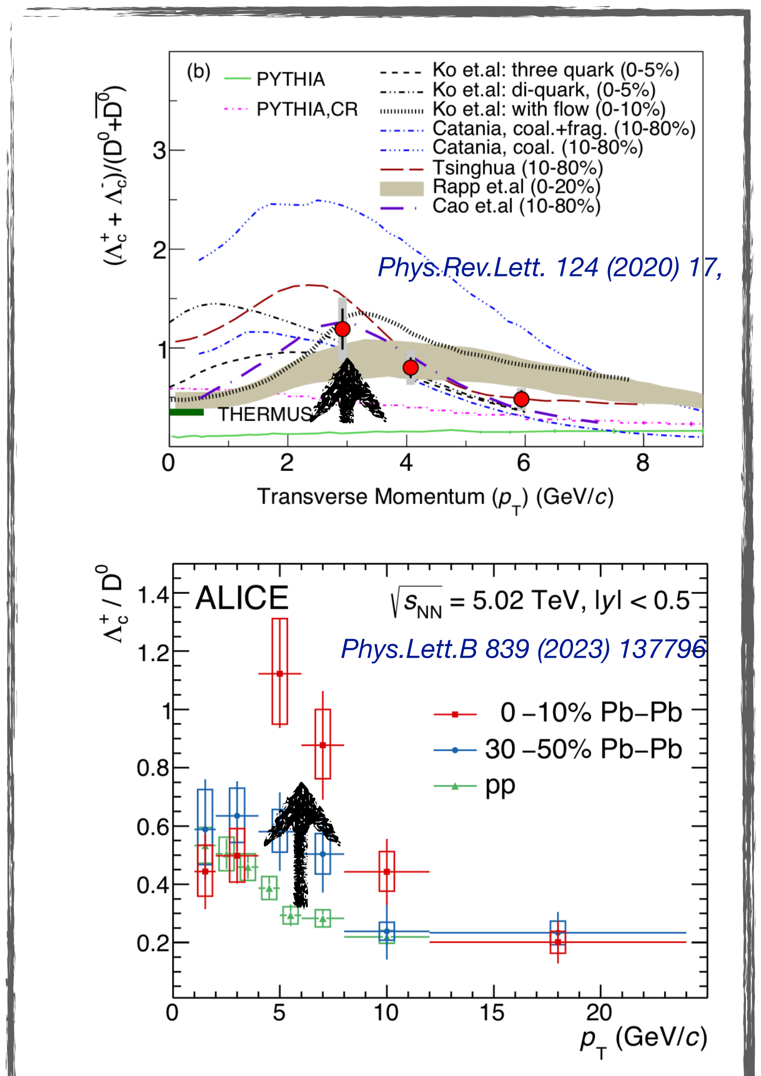
  Works well for e^+e^-, *low energy* pp,…

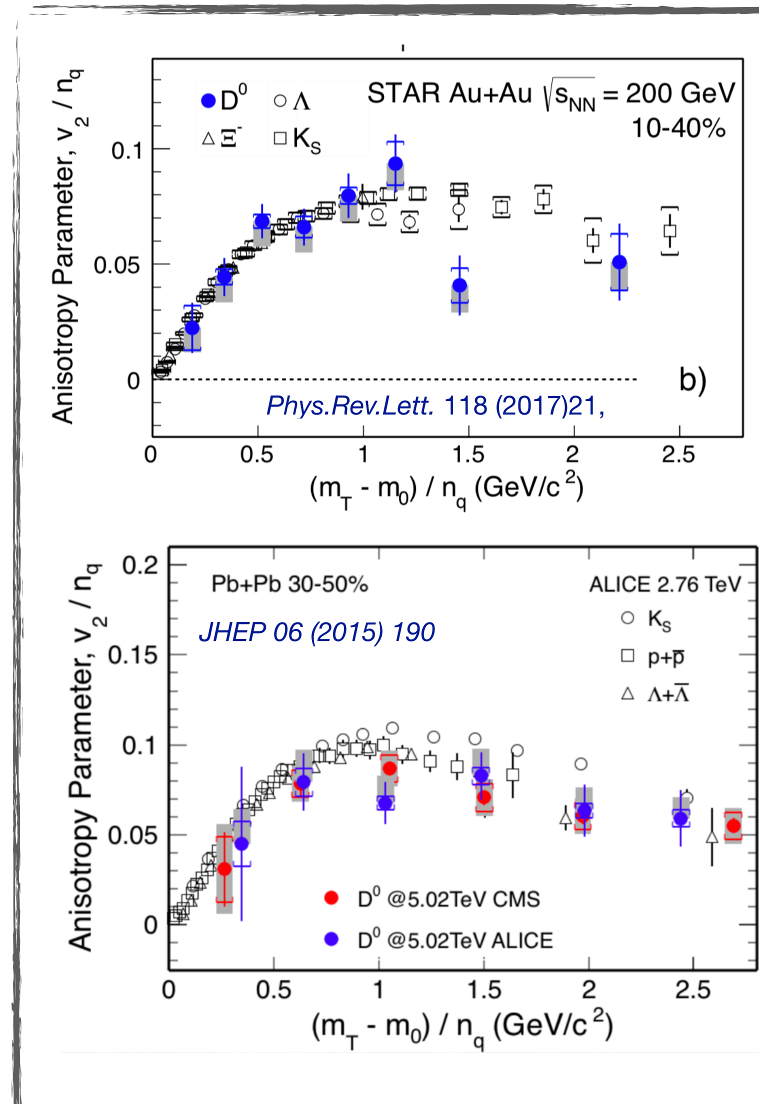
EPOS4HQ: heavy quark hadronization

When the local energy density is lower than the critical value (T~165MeV)

Heavy quarks hadronize into heavy flavor hadrons!

- ***Fragmentation***
- ***(Color)Recombination***





$$\frac{v_2(\text{meson})}{2} \approx \frac{v_2(\text{baryon})}{3}$$

- *Enhancement Baryon / Meson Ratio*
- *Quark Number Scaling of Elliptic flow*

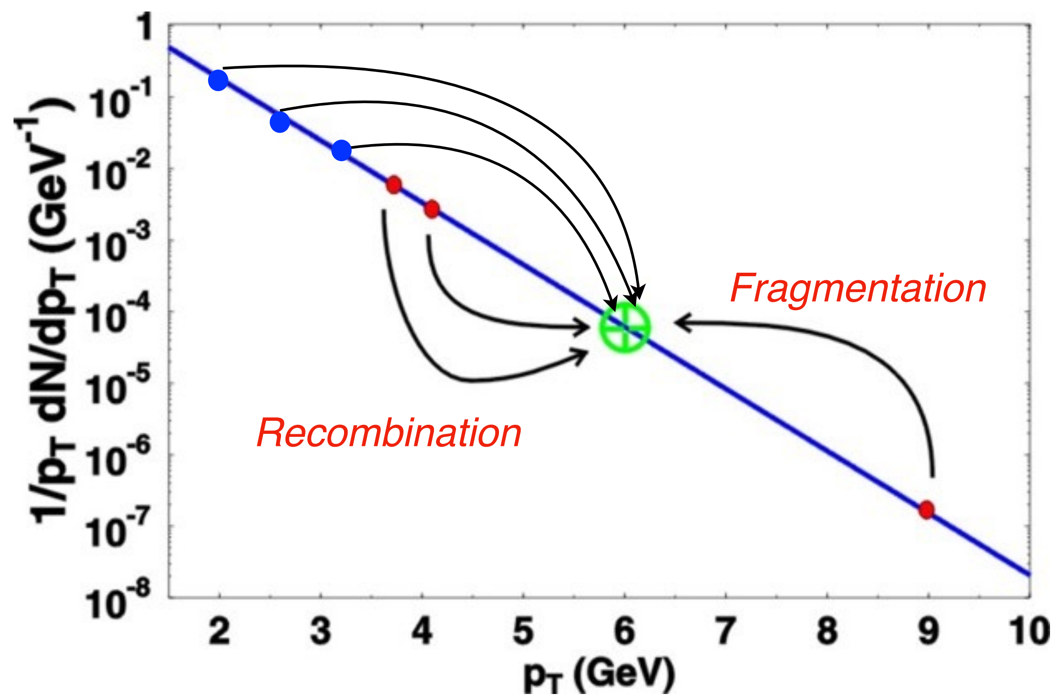
Hadronization in the hot medium shows a huge difference!

EPOS4HQ: heavy quark hadronization

When the local energy density is lower than the critical value (T~165MeV)

Heavy quarks hadronize into heavy flavor hadrons!

- ***Fragmentation***
- ***(Color)Recombination***



The heavy quark combines with the light quark(s) that are close together in phase space.

Low p_T heavy quark hadronizes by recombination while high p_T hadronizes by fragementation.

EPOS4HQ: heavy quark hadronization

When the local energy density is lower than the critical value (T~165MeV)

Heavy quarks hadronize via coalescence + fragmentation in EPOS4HQ!

EPOS4 with only string fragmentation

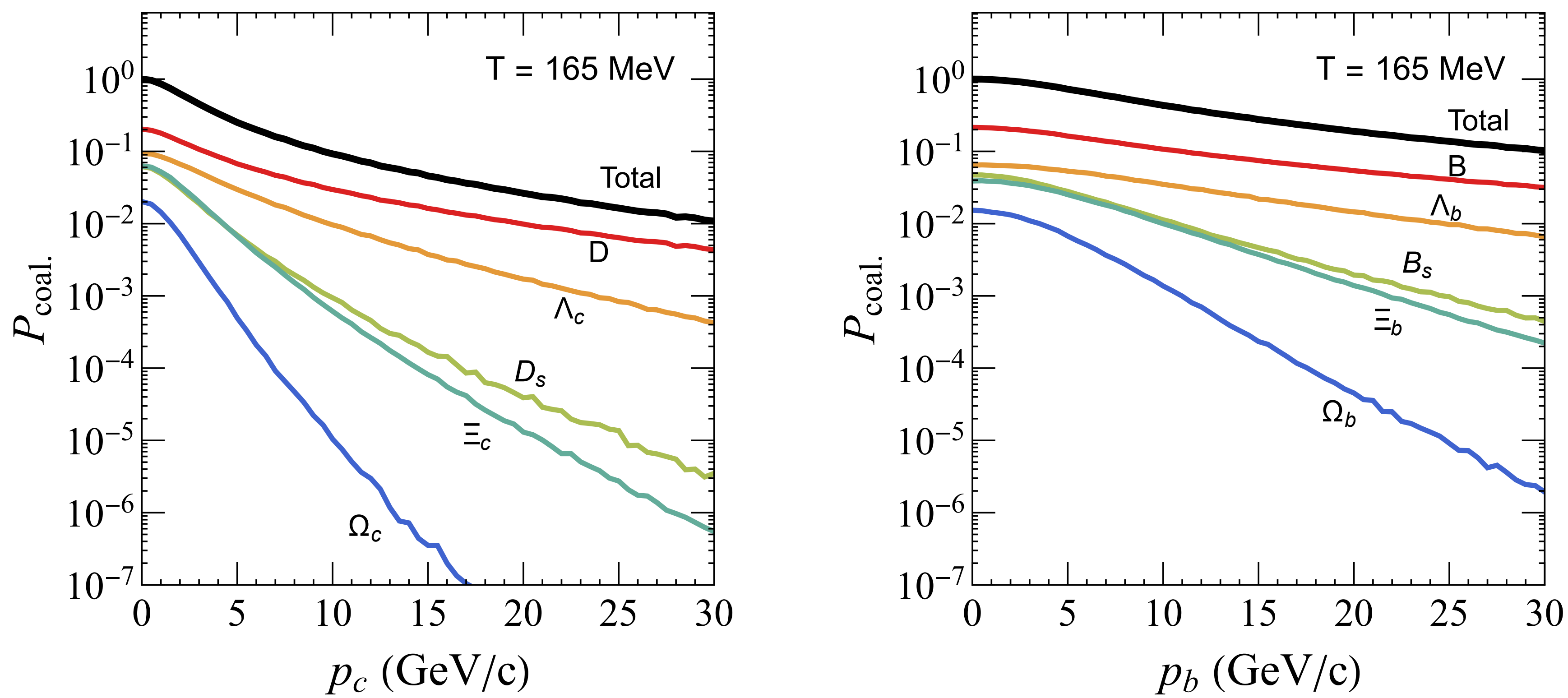
$$\frac{dN}{d^3\mathbf{P}} = g_H \sum_{N_Q} \int \prod_{i=1}^{k} \frac{d^3 p_i}{(2\pi)^3} f(\mathbf{p}_i) W_H(\mathbf{p}_1, \ldots, \mathbf{p}_i)\, \delta^{(3)}\left(\mathbf{P} - \sum_{i=1}^{N} \mathbf{p}_i\right),$$

$1 - P_{\mathrm{coal.}}$ *for fragmentation (HQET based fragmentation function)*

We include almost all hadrons (missing baryons predicted by the potential model; 17D,10D_s,38Λ_c,54Σ_c,92Ξ_c,54Ω_c; except the rare HF hadrons)

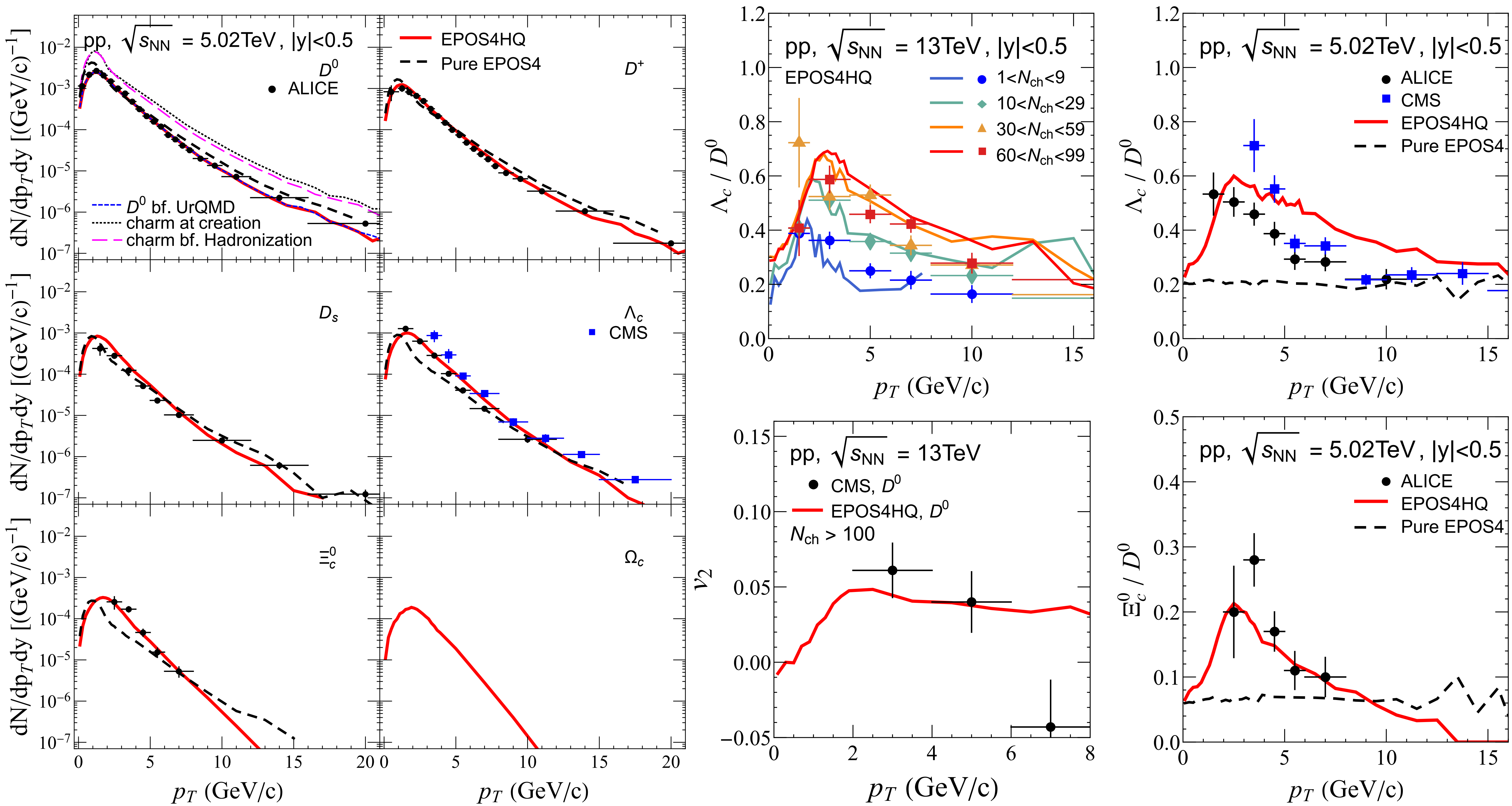
Ground states Wigner density: $W(p_r) = (2\sqrt{\pi}\sigma)^3 e^{-\sigma^2 p_r^2}$ *Width is given by the potential model*

Excited states are involved via the thermal ratio: $n_i = \frac{g_i}{2\pi^2} T_{\mathrm{FO}} m_i^2 K_2\left(\frac{m_i}{T_{\mathrm{FO}}}\right)$ $R^m = n^m_{\mathrm{excited}}/n_{\mathrm{ground}}.$



After hadronization, evolution in hadronic phase —> UrQMD

EPOS4HQ: @ pp

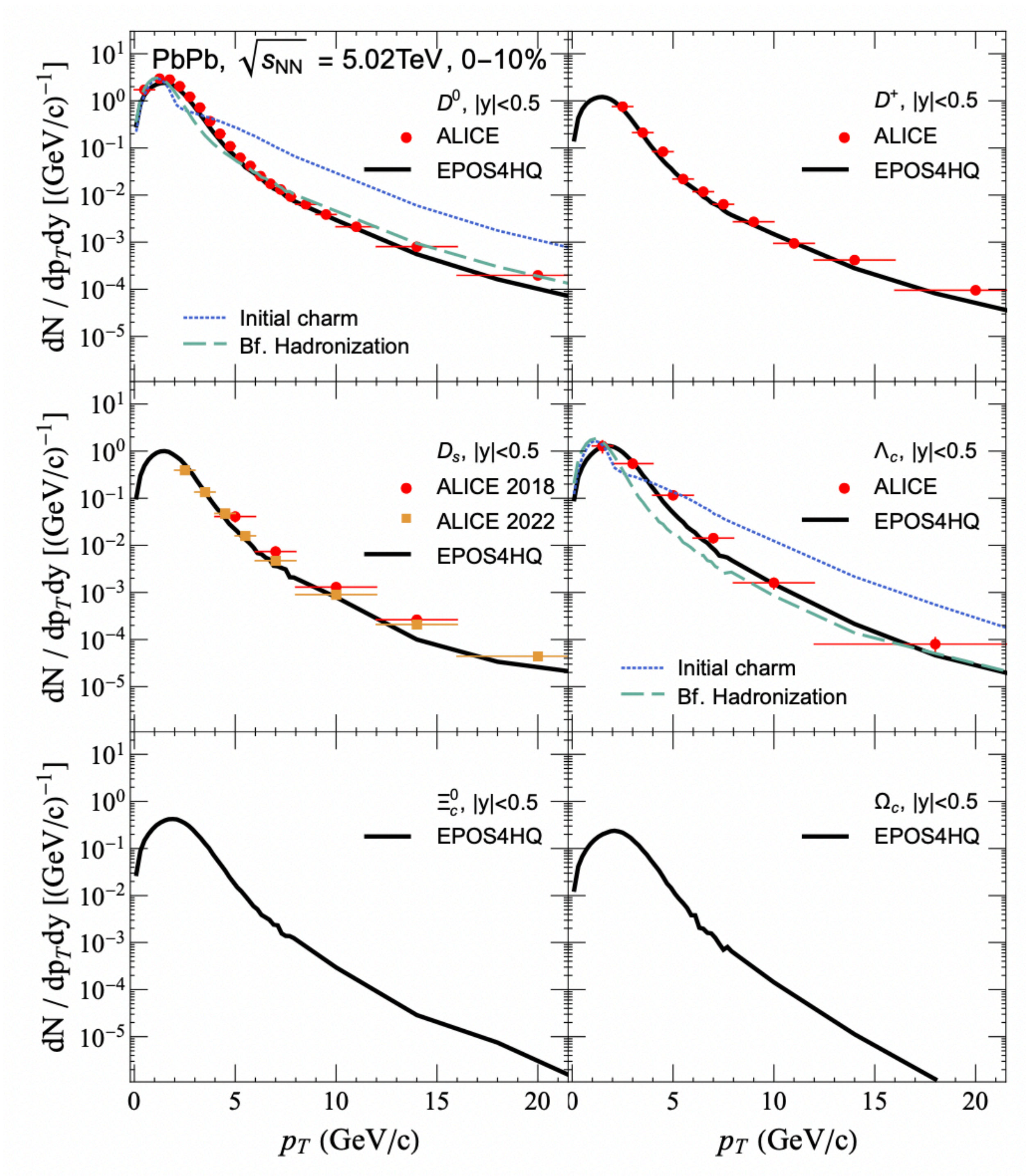


JZ, J.Aichelin, P.B. Gossiaux, K.Werner, Phys.Rev.D 109 (2024) 5, 054011

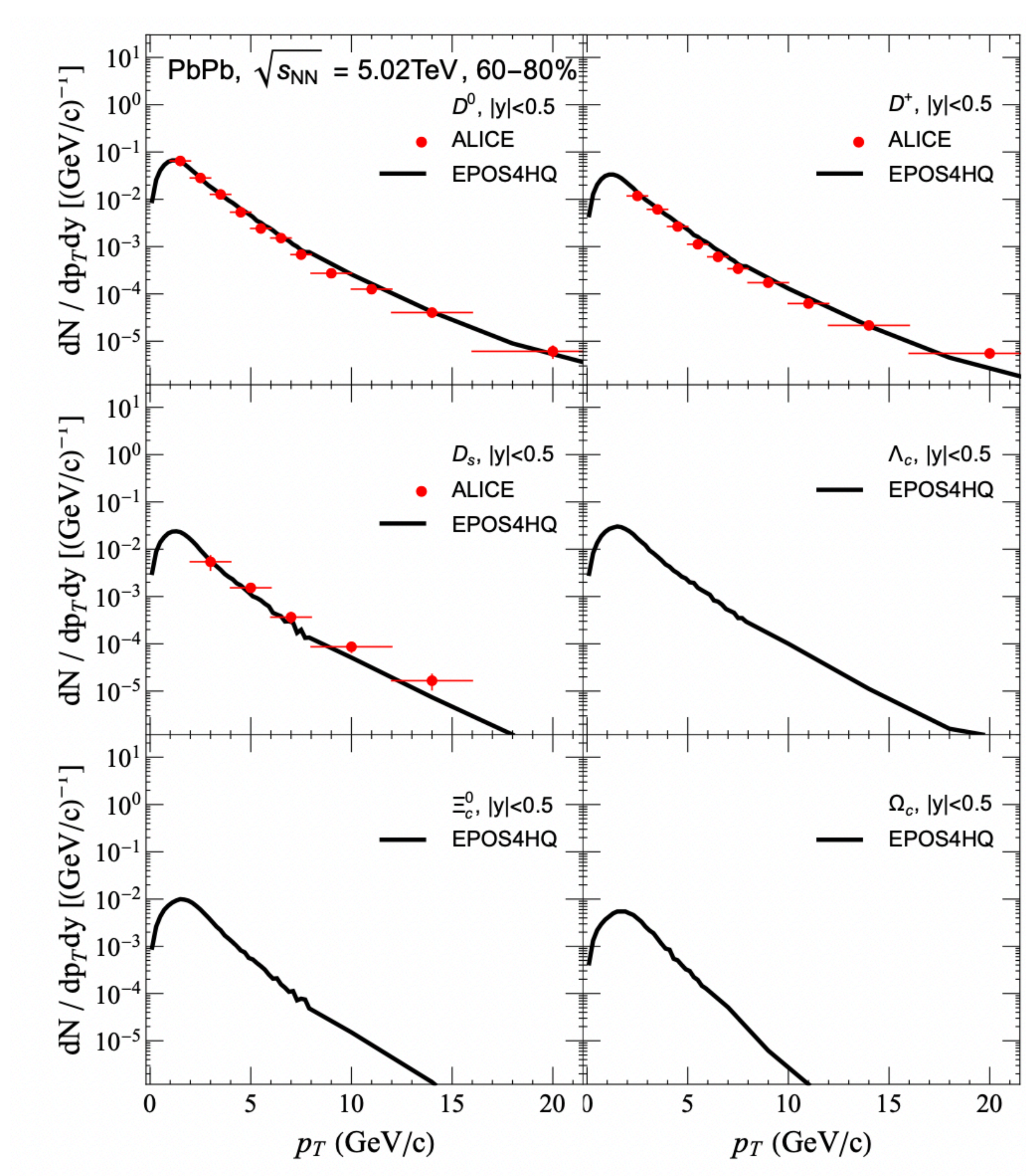
Spectra, multiplicity dependent observables, yield ratios, v_2 can be explained well!

EPOS4HQ: @ AA

Central collisions



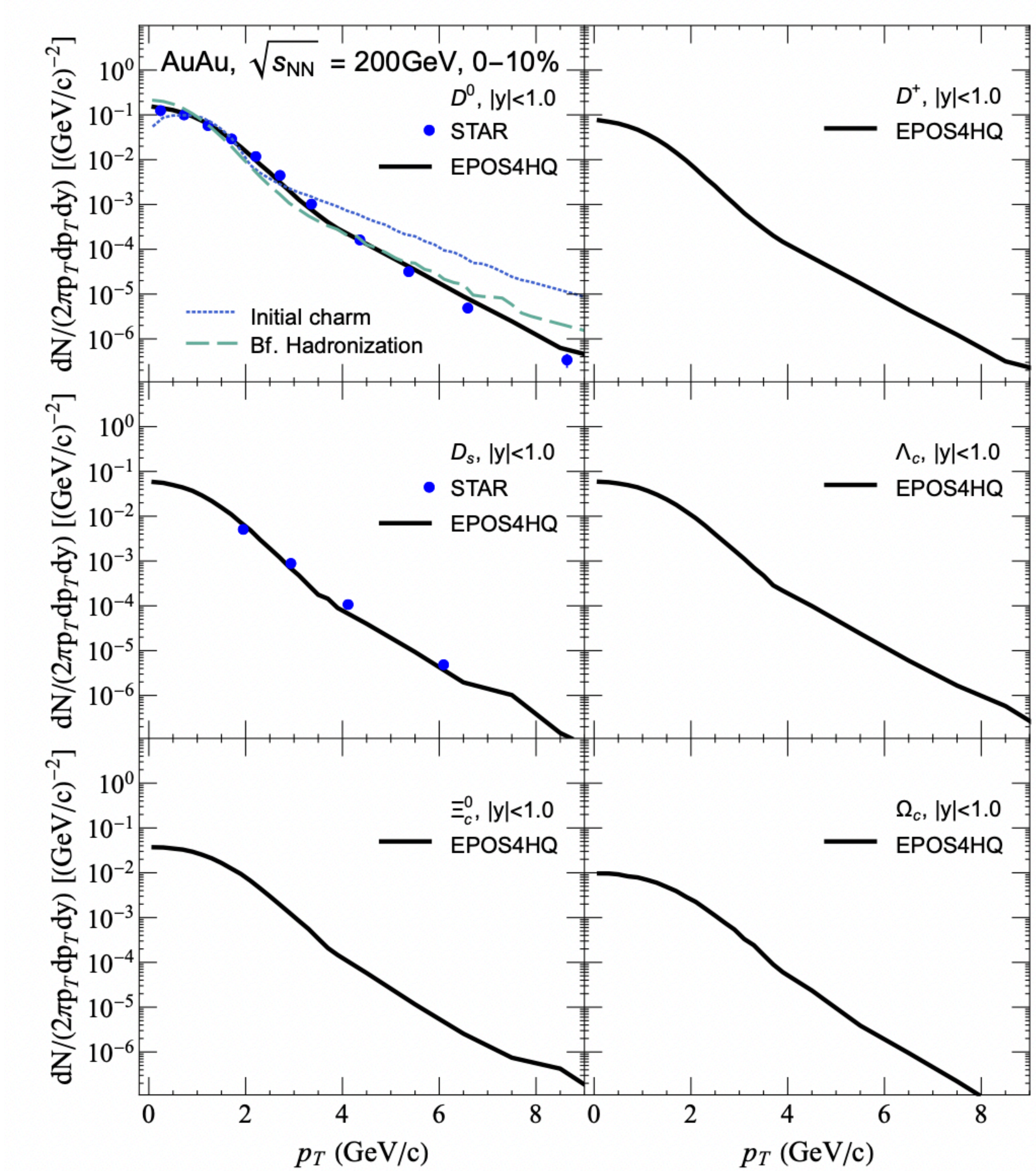
Peripheral collisions



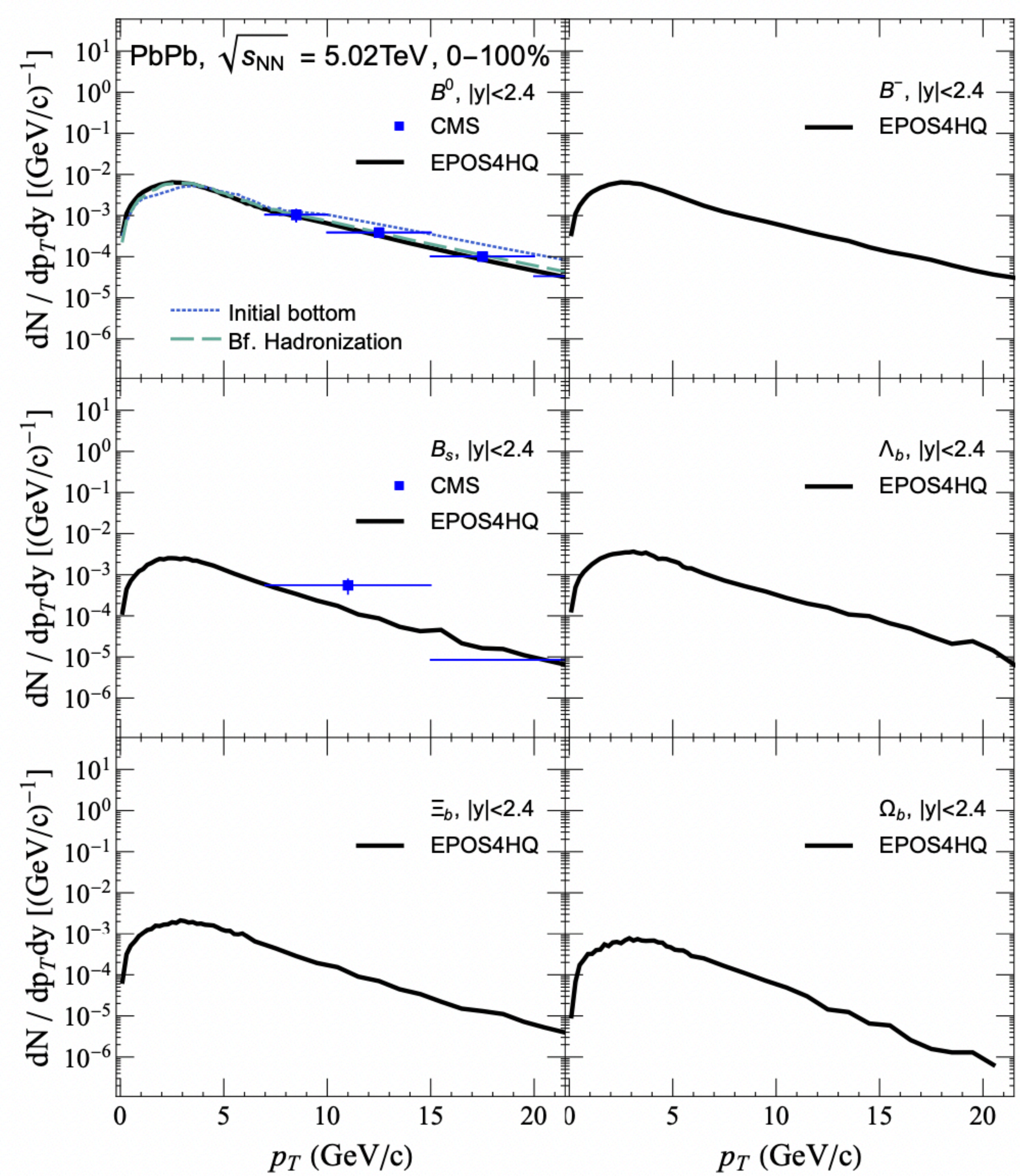
***JZ,** J.Aichelin, P.B. Gossiaux, V. Ozvenchuk, K.Werner, arXiv:2401.17096*

EPOS4HQ: @ AA

RHIC energy



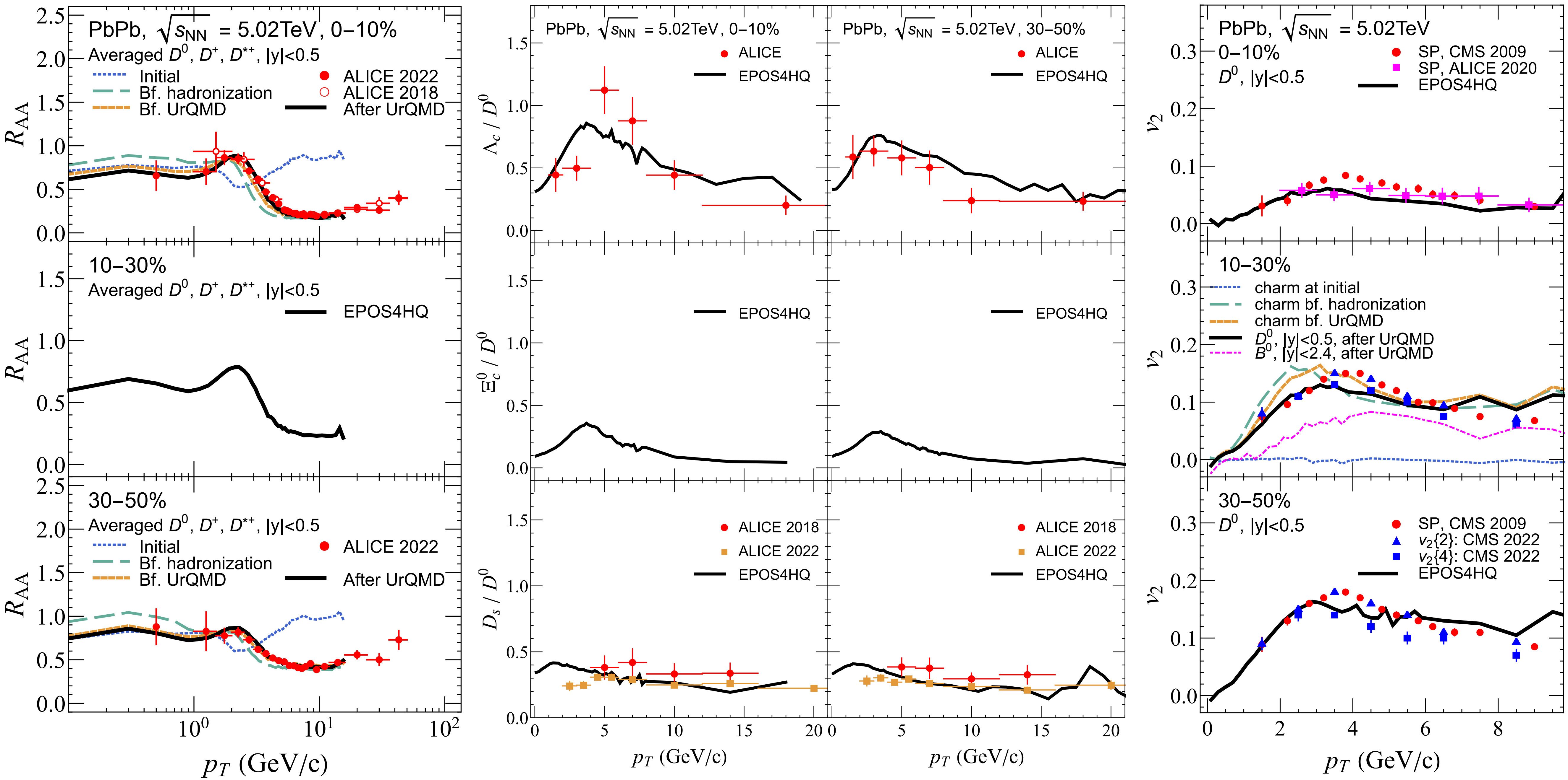
Bottom sector



***JZ,** J.Aichelin, P.B. Gossiaux, V. Ozvenchuk, K.Werner, arXiv:2401.17096*

EPOS4HQ: @ AA

R_{AA} — *Yield ratios* — v_2

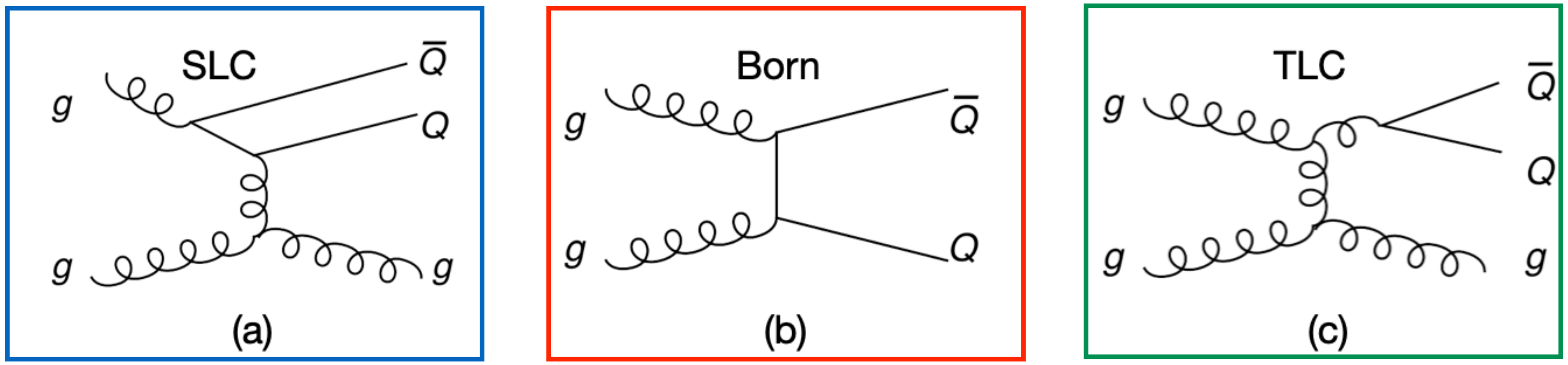


JZ, *J.Aichelin, P.B. Gossiaux, V. Ozvenchuk, K.Werner, arXiv:2401.17096*

Outline

- A brief Introduction to EPOS4
- Open heavy flavor production in EPOS4
- **Quarkonium production in EPOS4**

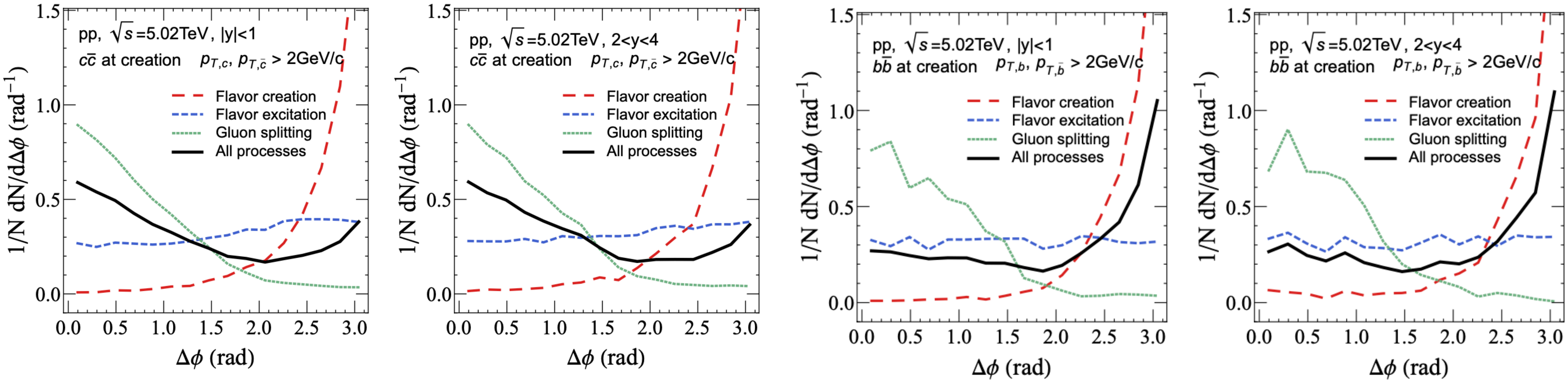
Heavy quark correlations



Flavor excitation

Flavor creation

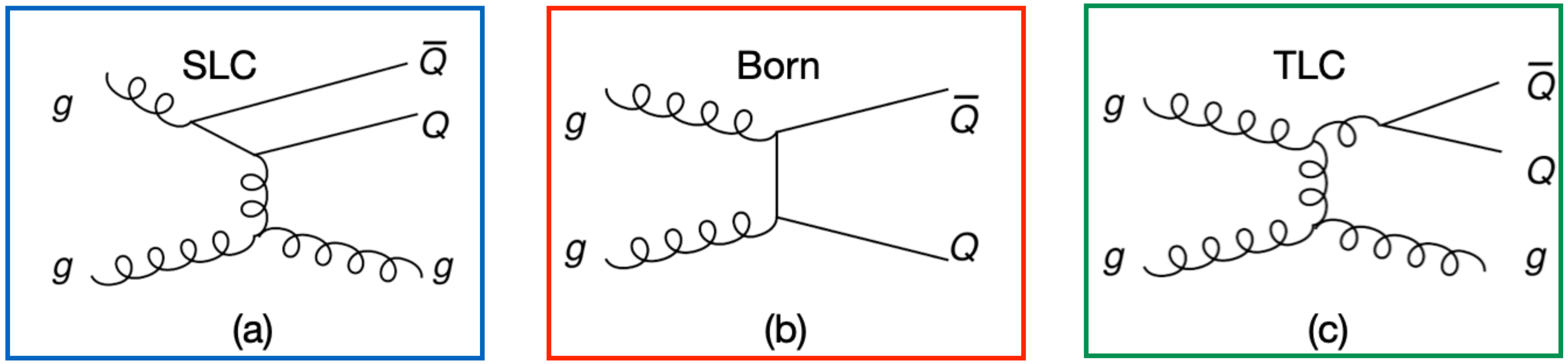
Gluon splitting



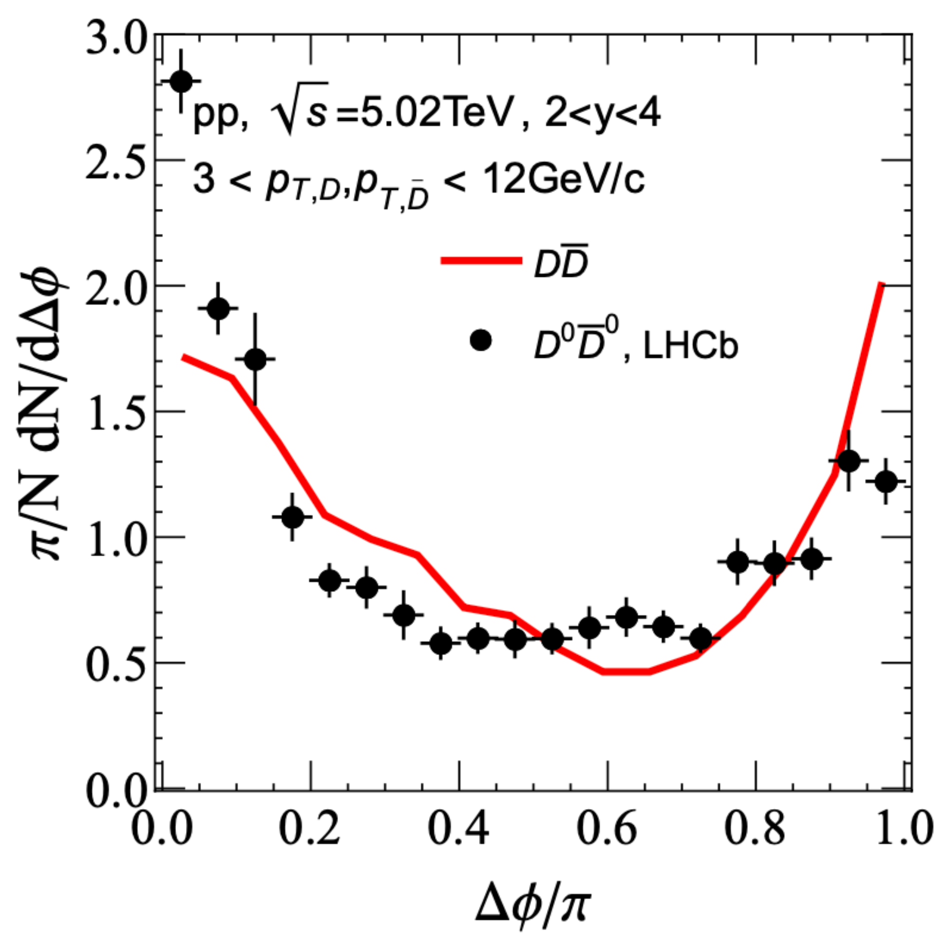
$c\bar{c}$ correlations

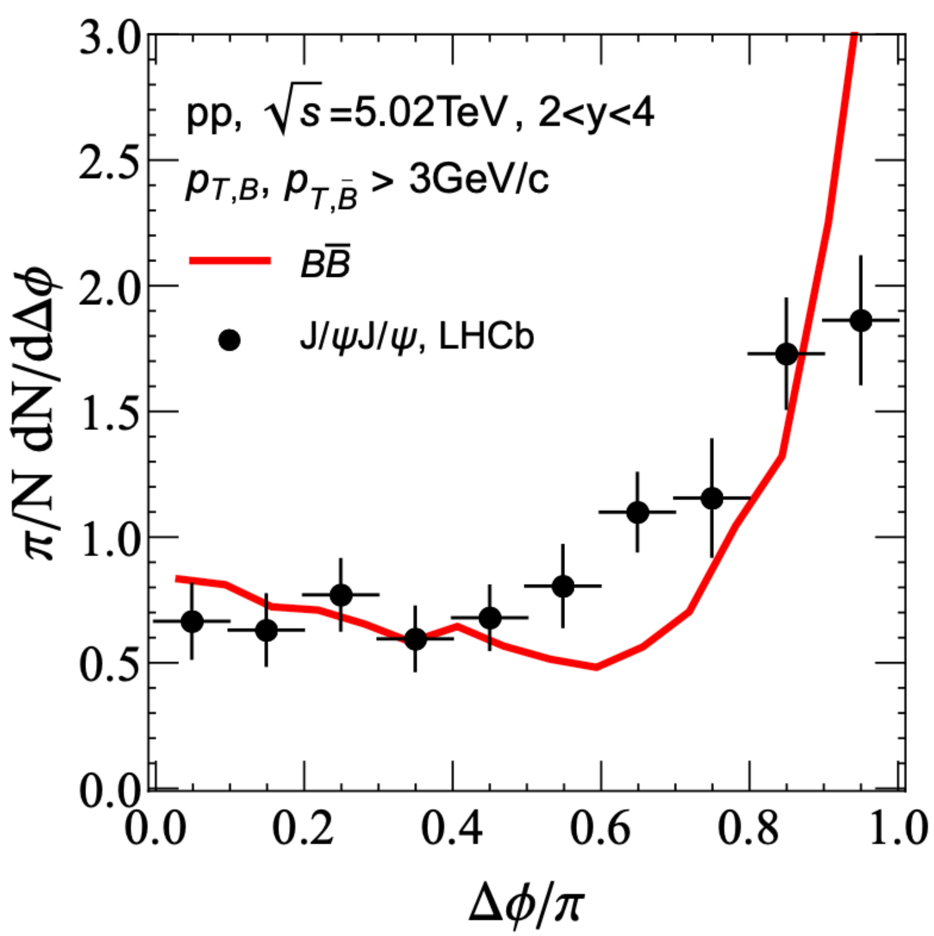
$b\bar{b}$ correlations

Heavy quark correlations



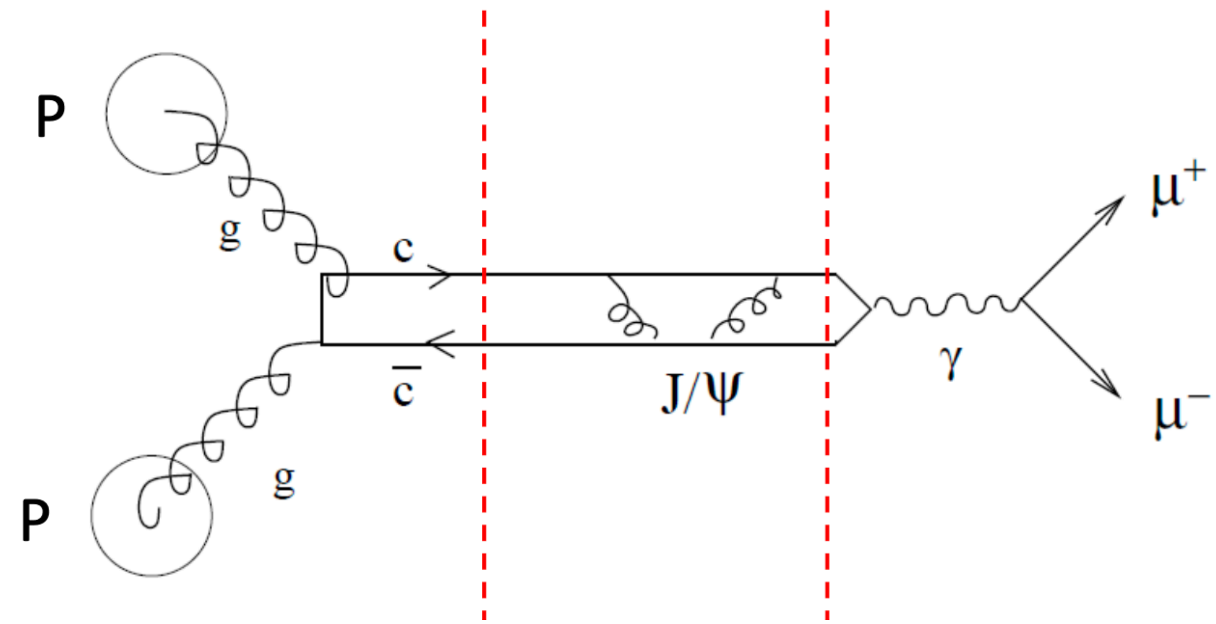
Flavor excitation   *Flavor creation*   *Gluon splitting*





$D\bar{D}$ correlations   ***$B\bar{B}$ correlations***

Quarkonium production in pp collisions



Perturbative part ***Non-perturbative part*** ***Decays***

- *Color evaporation model (CEM)*
  R.Vogt, V. Cheung, Y. Ma, H. Fritzsch,…
- *Color singlet model (CSM)*
  C.H. Chang, E. Berger, D. Jones, R. Baier,…
- *Color octet model (COM)*
  G.T. Bodwin, E. Braaten, T.C. Yuan, G. Lepage,…
- *Non-relativistic QCD model (NRQCD)*
  Y. Ma. H.S. Shao, K.Chao, R. Venugopala, M.Butenschoen, B.Kniehl ,C.H. Chang, J. Wang…
- ***Wigner density matrix formalism***
  *T. Song, **JZ**, P.B. Gossiaux, E. Bratkovskaya, J. Aichelin,…*

Quarkonium production in pp collisions

Wigner density matrix formalism —> density matrix projection

$$P^{\Phi}(t) = \mathrm{Tr}[\rho^{\Phi}\hat{\rho}_{\mathrm{tot}}]$$

density matrix of the quarkonium (for ρ^{Φ}) — *density matrix of N quarks and antiquarks system* (for $\hat{\rho}_{\mathrm{tot}}$)

In phase-space, the differential production probability:

$$\frac{dP_{nl}}{d^3P} = g\sum\int\frac{d^3R\,d^3r\,d^3p}{(2\pi\hbar)^6}W^{\Phi}_{nl}(\mathbf{r},\mathbf{p})\prod_{j>2}\int\frac{d^3r_jd^3p_j}{(2\pi\hbar)^{3(N-2)}}W^{(N)}(\mathbf{r}_1,\mathbf{p}_1,\mathbf{r}_2,\mathbf{p}_2,\ldots,\mathbf{r}_N,\mathbf{p}_N)$$

Wigner density of the quarkonium (for $W^{\Phi}_{nl}(\mathbf{r},\mathbf{p})$)

Wigner representation of the ensemble of N heavy quarks produced in a pp collision (for $W^{(N)}$)

Assume that the unknown quantal N-body Wigner density can be replaced by the average of classical phase space distributions: $W^{(N)} \approx \langle W^{(N)}_{\mathrm{classical}}\rangle$. *Classical momentum space distribution of the heavy quarks can be provided by EPOS4, PYTHIA, …. The relative distance in their center-of-mass frame is given by a Gaussian distribution.* ***Only one "free" parameter*** $\sigma_{Q\bar{Q}}$

$$\sigma_{Q\bar{Q}} \sim 1/p_r$$

JZ, *P.B. Gossiaux, T. Song, E. Bratkovskaya, J. Aichelin. arXiv: 2312.11349.*

D. Villar, ***JZ,*** *J. Aichelin, P.B. Gossiaux. Phys.Rev.C 107 (2023) 5, 054913*

T. Song, J. Aichelin, E. Bratkovskaya. PRC 96 (2017) 1, 014907.

T. Song, J. Aichelin, ***JZ,*** *P.B. Gossiaux, E. Bratkovskaya. PRC 108 (2023) 5, 054908*

Quarkonium Wigner function

The Wigner function can be constructed via a Wigner transformation in the spherical coordinate.

JZ, P.B. Gossiaux, T. Song, E. Bratkovskaya, J. Aichelin. arXiv: 2312.11349.

$$W_{1S}(\mathbf{r},\mathbf{p}) = 8e^{-\xi},$$

$$W_{1P}(\mathbf{r},\mathbf{p}) = \frac{8}{3}e^{-\xi}\Big(2\xi - 3\Big),$$

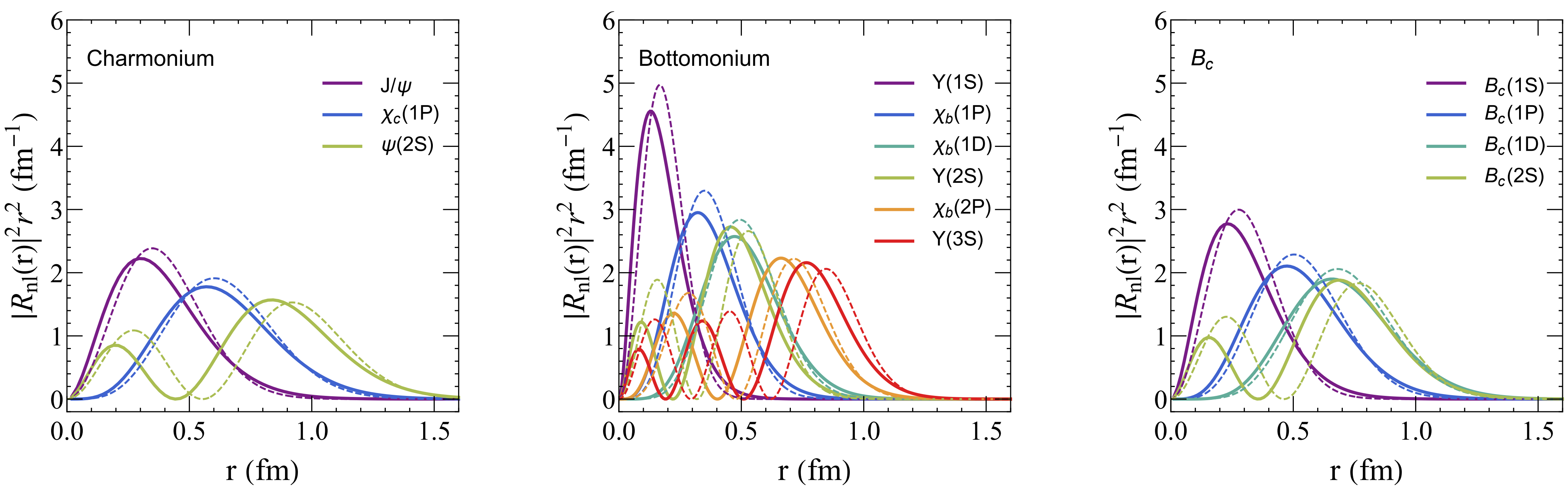
$$W_{1D}(\mathbf{r},\mathbf{p}) = \frac{8}{15}e^{-\xi}\Big(15 + 4\xi^2 - 20\xi + 8[p^2r^2 - (\mathbf{p}\cdot\mathbf{r})^2]\Big),$$

$$W_{2S}(\mathbf{r},\mathbf{p}) = \frac{8}{3}e^{-\xi}\Big(3 + 2\xi^2 - 4\xi - 8[p^2r^2 - (\mathbf{p}\cdot\mathbf{r})^2)]\Big),$$

$$W_{2P}(\mathbf{r},\mathbf{p}) = \frac{8}{15}e^{-\xi}\Big(-15 + 4\xi^3 - 22\xi^2 + 30\xi - 8(2\xi - 7)[p^2r^2 - (\mathbf{p}\cdot\mathbf{r})^2]\Big),$$

$$\begin{aligned} W_{3S}(\mathbf{r},\mathbf{p}) = \frac{8}{315}e^{-\xi}\Big(&315 + 42\xi^4 - 336\xi^3 + 924\xi^2 - 840\xi \\ &- [2009 + 32p^2r^2 + 336r^4/\sigma^4 - 1400r^2/\sigma^2 - 896p^2\sigma^2 + 224p^4\sigma^4][p^2r^2 - (\mathbf{p}\cdot\mathbf{r})^2] \\ &- [686 + 608p^2r^2 + 112r^2/\sigma^2 - 896p^2\sigma^2 + 224p^4\sigma^4 - 672(\mathbf{p}\cdot\mathbf{r})^2](\mathbf{p}\cdot\mathbf{r})^2\Big), \end{aligned}$$

$\xi = \frac{r^2}{\sigma^2} + p^2\sigma^2.$ *Wigner function of excited states depends not only on the |**r**| and |**p**|, but also the angle between them.*



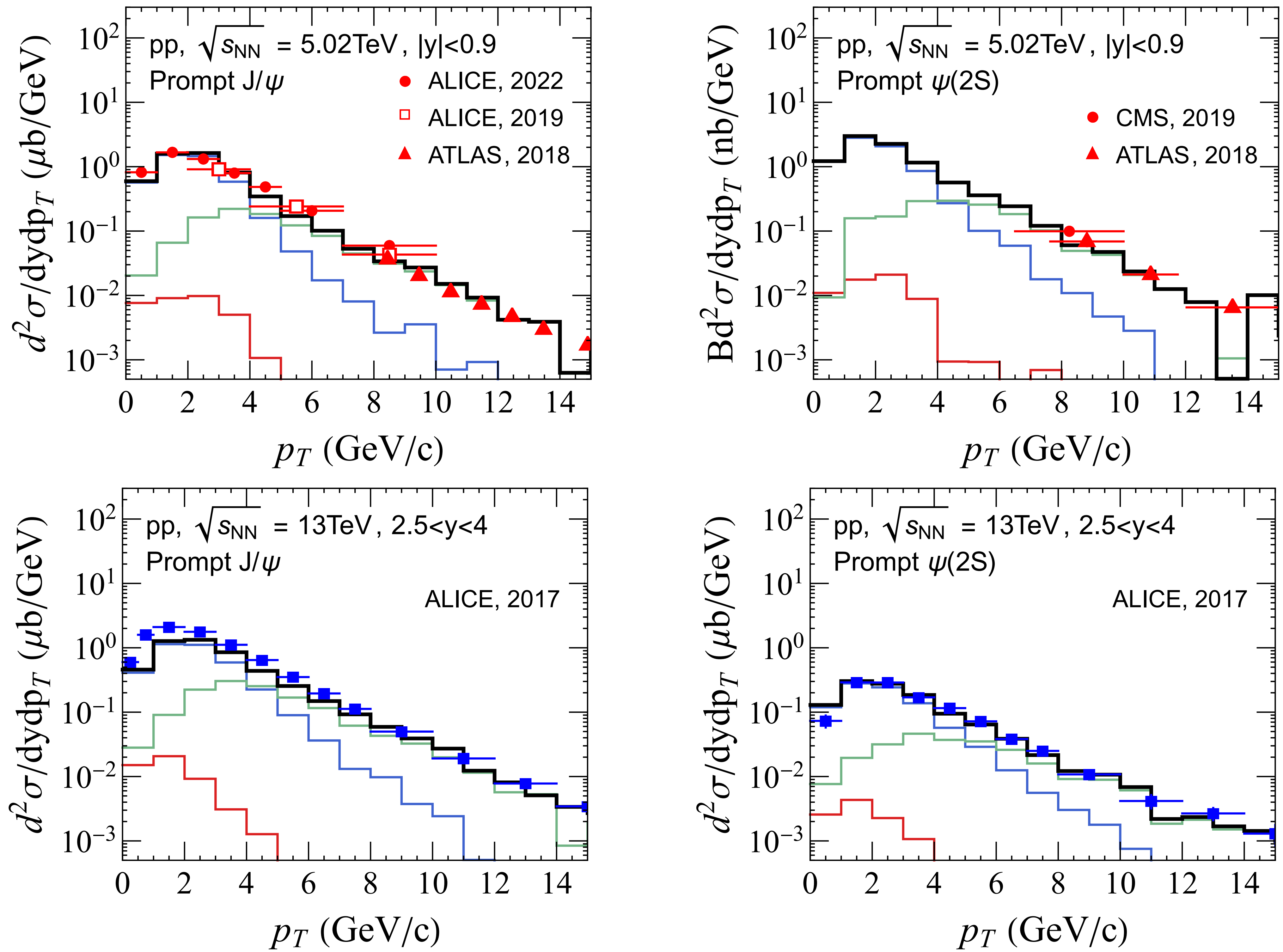
Widths are chosen to match the root-mean-square radius $\langle r^2 \rangle$ of the real quarkonium wave function !

Charmonium production in pp collisions

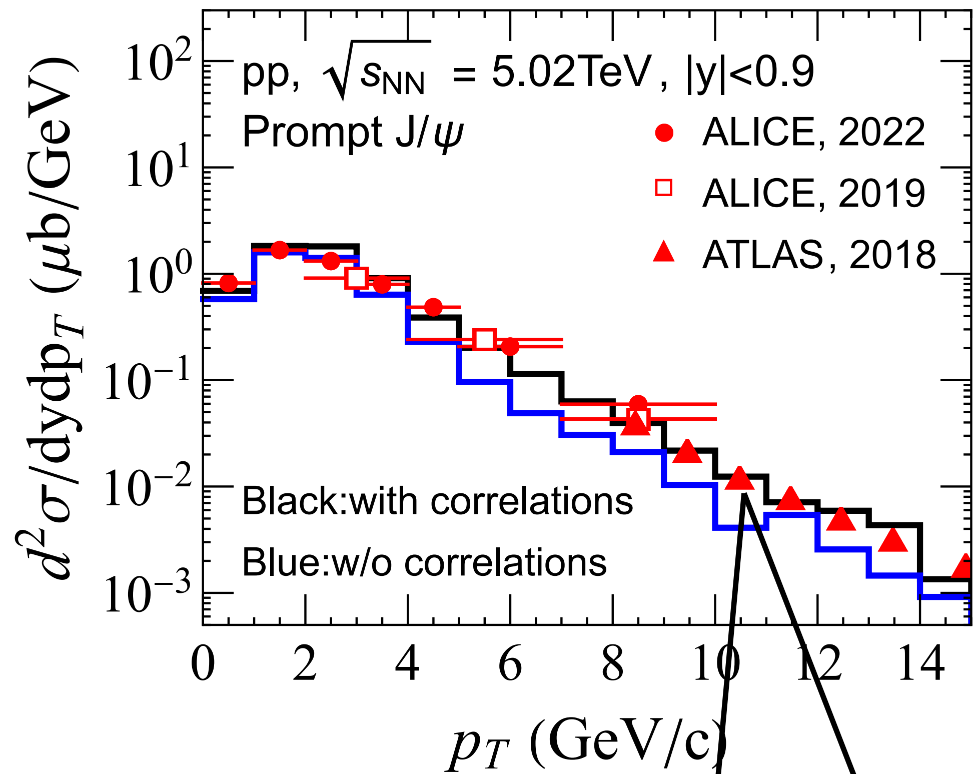
Prompt $J/\psi = J/\psi + \chi_c \times 30\% + \psi(2S) \times 61\%$

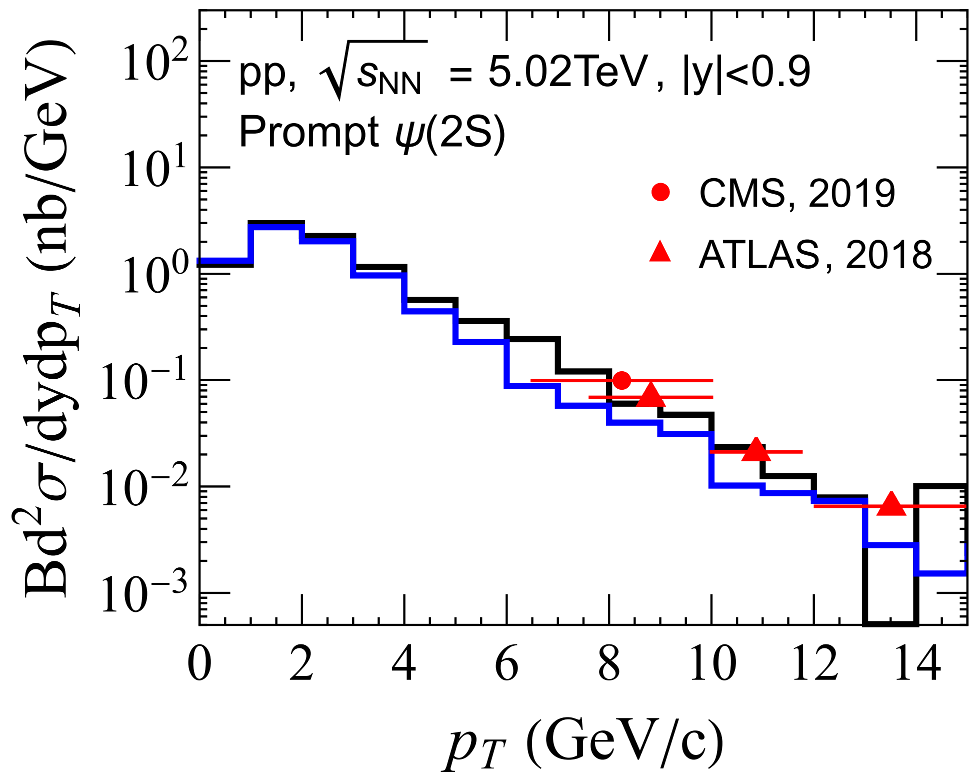
Prompt $\psi(2S) = \psi(2S)$

Black: prompt; Red: flavor creation; Blue: flavor excitation; Green: gluon splitting

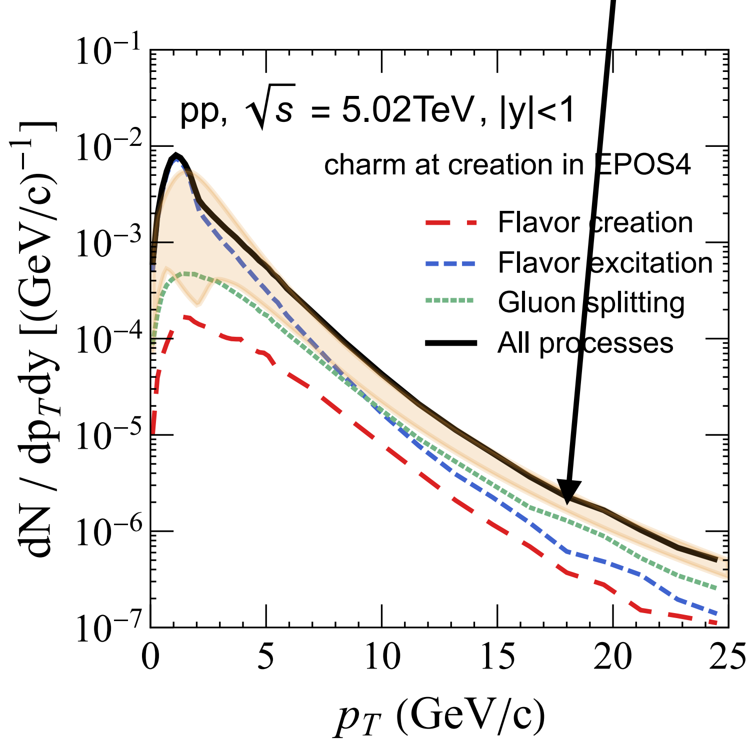


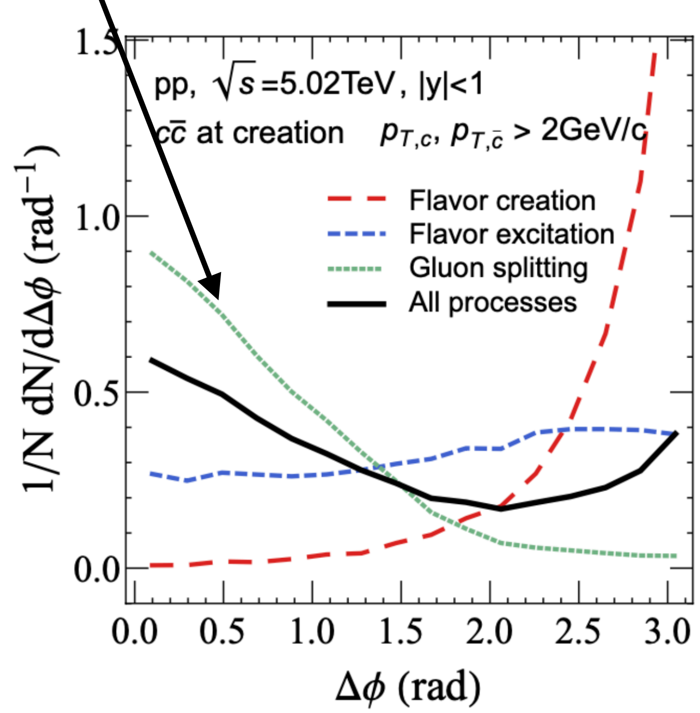
Charmonium production in pp collisions





If we artificially erase the correlation between c and $\bar{c}$, we find the results underestimate the exp. data especially in the high p_T region!





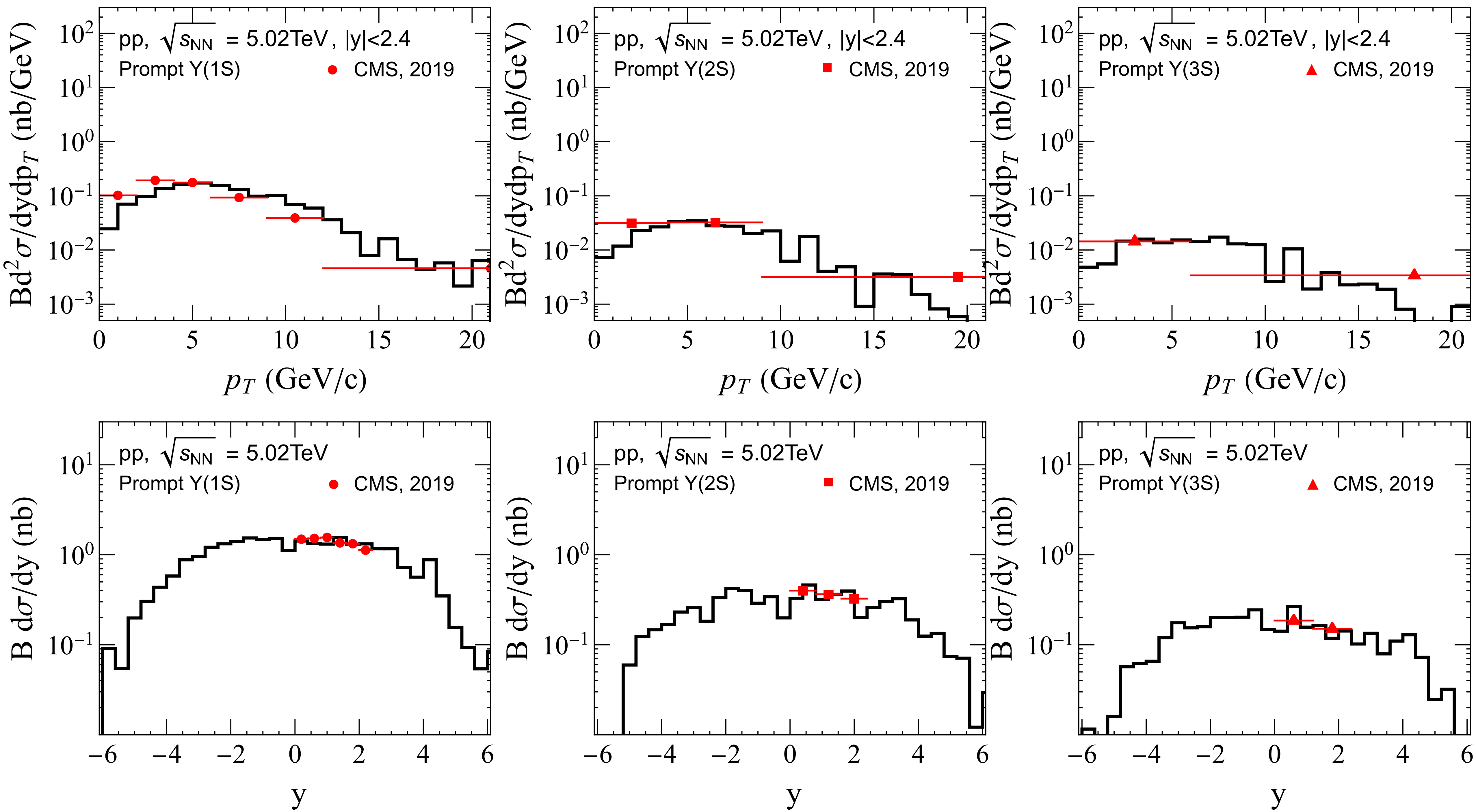
heavy quark correlation is important for the quarkonium production!

Bottomonium production in pp collisions

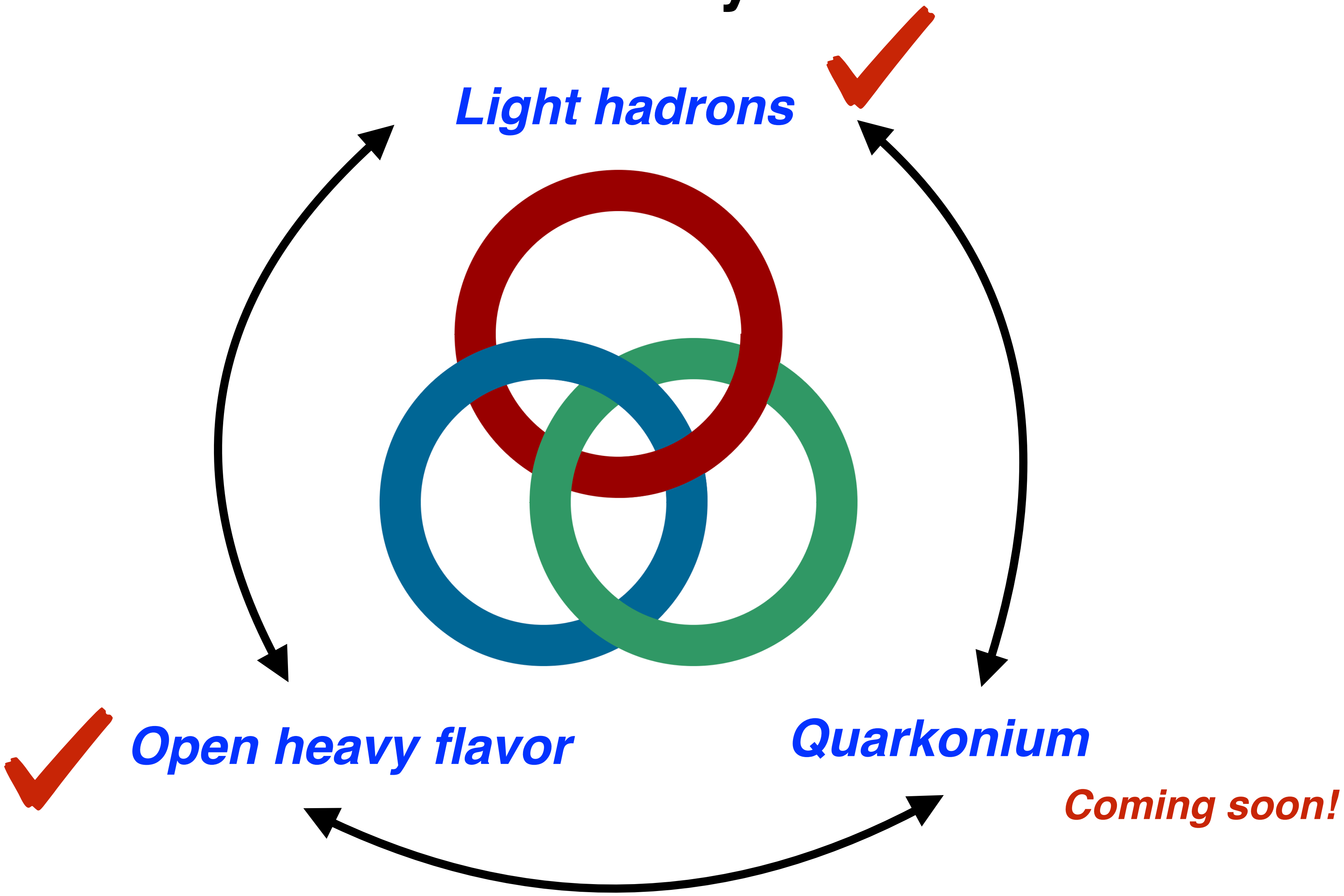
Prompt $\Upsilon(1S)$ = $\Upsilon(1S)$ + $\chi_b(1P)$ x 23% + $\chi_b(1D)$ x 20% + $\Upsilon(2S)$ x 7% + $\chi_b(2P)$ x 7% + $\Upsilon(3S)$ x 1%

Prompt $\Upsilon(2S)$ = $\Upsilon(2S)$ + $\chi_b(2P)$ x 9.3% + $\Upsilon(3S)$ x 10.6%

Prompt $\Upsilon(3S)$ = $\Upsilon(3S)$



Summary



- *To a unified framework to describe at the same time of light, open heavy flavor, and quarkonium!*

A public version with heavy quark, EPOS4HQ will be released soon.

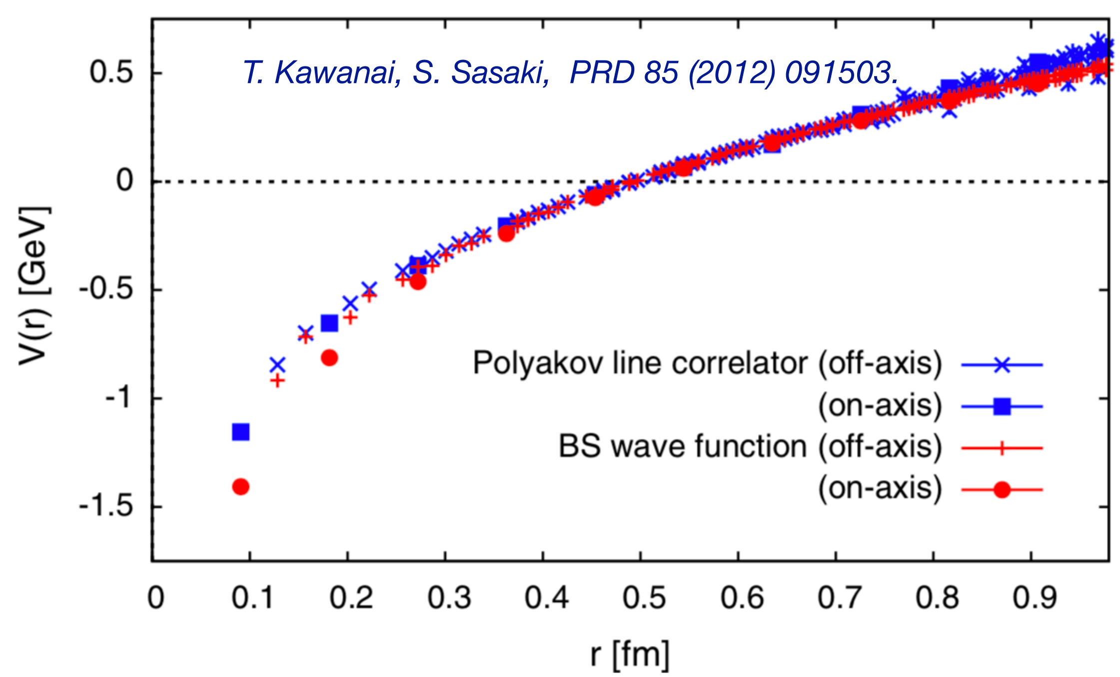
Thanks for your attention!

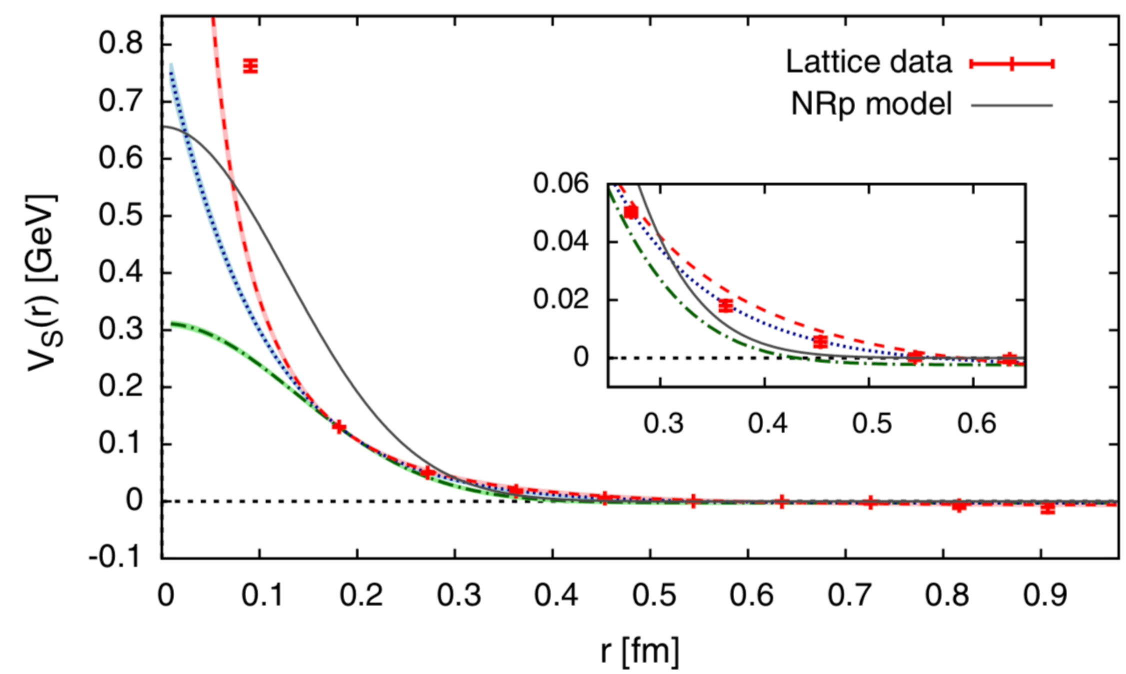
backup

Quarkonium static properties in a vacuum

Two-body Schroedinger equation: $$\left[\frac{\hat{p}_1^2}{2m_1}+\frac{\hat{p}_2^2}{2m_2}+V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{s}_1,\mathbf{s}_2)\right]\psi = E\psi$$

Cornell potential + Spin-spin interaction





States	$\eta_c(1S)$	$J/\psi(1S)$	$h_c(1P)$	$\chi_c(1P)$	$\eta_c(2S)$	$\psi(2S)$	$h_c(2P)$	$\chi_c(2P)$
$M_{Exp.}$(GeV)	2.981	3.097	3.525	3.556	3.639	3.686	-	3.927
$M_{Th.}$(GeV)	2.967	3.102	3.480	3.500	3.654	3.720	3.990	4.000
$\langle r\rangle$(fm)	0.365	0.427	0.635	0.655	0.772	0.802	0.961	0.980
States	$\eta_b(1S)$	$\Upsilon(1S)$	$h_b(1P)$	$\chi_b(1P)$	$\eta_b(2S)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
$M_{Exp.}$(GeV)	9.398	9.460	9.898	9.912	9.999	10.023	10.269	10.355
$M_{Th.}$(GeV)	9.397	9.459	9.845	9.860	9.957	9.977	10.221	10.325
$\langle r\rangle$(fm)	0.200	0.214	0.377	0.387	0.465	0.474	0.603	0.680

***JZ**, K. Zhou, S. Chen, P. Zhuang, PPNP. 114 (2020) 103801.*

Can explain the exp. mass very well!

Quarkonium Wigner function

The Wigner function of quarkonium can be constructed by their wave function.

$$\left[-\frac{1}{2\mu}\left(\frac{d^2}{dr^2}+\frac{2}{2}\frac{d}{dr}\right)+\frac{l(l+1)}{2\mu r^2}+V(r)\right]R_{nl}(r)=ER_{nl}(r),$$

Cornell potential + Spin-spin interaction

Approximate the wave function by a 3-D isotropic harmonic oscillator wave function

$$\psi_{nlm}(r,\theta,\phi)=R_{nl}(r)Y_{l,m}(\theta,\phi) \qquad R_{nl}(r)=\left[\frac{2(n!)}{\sigma^3\Gamma(n+l+3/2)}\right]^{\frac{1}{2}}\left(\frac{r}{\sigma}\right)^l e^{-\frac{r^2}{2\sigma^2}}L_n^{l+1/2}\left(\frac{r^2}{\sigma^2}\right),$$

Widths are chosen to match the root-mean-square radius $\langle r^2\rangle$ *of the real quarkonium wave function !*

$$\langle r^2\rangle_{1S}=3\sigma^2/2,\quad \langle r^2\rangle_{1P}=5\sigma^2/2,\quad \langle r^2\rangle_{1D}=7\sigma^2/2,$$
$$\langle r^2\rangle_{2S}=7\sigma^2/2,\quad \langle r^2\rangle_{2P}=9\sigma^2/2,\quad \langle r^2\rangle_{3S}=11\sigma^2/2.$$

Real quarkonium wavefunction by solving the Schroeding eq.

	J/ψ	$\chi_c(1P)$	$\psi(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\chi_b(1D)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$	$B_c(1S)$	$B_c(1P)$	$B_c(1D)$	$B_c(2S)$
$\langle r^2\rangle(\mathrm{fm}^2)$	0.182	0.453	0.714	0.042	0.153	0.284	0.236	0.410	0.520	0.115	0.316	0.542	0.497
$\sigma(\mathrm{fm})$	0.348	0.426	0.452	0.167	0.247	0.285	0.260	0.302	0.307	0.277	0.356	0.393	0.377

Parameter in the sotropic harmonic oscillator wave function

Charmed/bottom mesons

D *17 states*

Charmed Mesons (C = + −1)
D+ −
D0
D*(2007)0
D*(2010)+ −
D*(0)(2400)0
D*(0)(2400)+ −
D(1)(2420)0
D(1)(2420)+ −
D(1)(2430)0
D*(2)(2460)0
D*(2)(2460)+ −
D(2550)0
D*(J)(2600)
D*(2640)+ −
D(2740)0
D(2750)
D(3000)0

D_s *10 states*

Charmed, Strange Mesons (C = S = +−1)
D(s)+−
D*(s)+−
D*(s0)(2317)+−
D(s1)(2460)+−
D(s1)(2536)+−
D(s2)(2573)+−
D*(s1)(2700)+−
D*(s1)(2860)+−
D*(s3)(2860)+−
D(sJ)(3040)+−

Particle data Group

Charmed/bottom baryons

Σ_c

54 states

38 states

Λ_c

TABLE II: Masses of the Λ_Q $(Q = c, b)$ heavy baryons (in MeV).

		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	M^{exp} [1]	M	M^{exp} [1]
$0(\frac{1}{2}^+)$	$1S$	2286	2286.46(14)	5620	5620.2(1.6)
$0(\frac{1}{2}^+)$	$2S$	2769	2766.6(2.4)?	6089	
$0(\frac{1}{2}^+)$	$3S$	3130		6455	
$0(\frac{1}{2}^+)$	$4S$	3437		6756	
$0(\frac{1}{2}^+)$	$5S$	3715		7015	
$0(\frac{1}{2}^+)$	$6S$	3973		7256	
$0(\frac{1}{2}^-)$	$1P$	2598	2595.4(6)	5930	
$0(\frac{1}{2}^-)$	$2P$	2983	$2939.3(^{1.4}_{1.5})$?	6326	
$0(\frac{1}{2}^-)$	$3P$	3303		6645	
$0(\frac{1}{2}^-)$	$4P$	3588		6917	
$0(\frac{1}{2}^-)$	$5P$	3852		7157	
$0(\frac{3}{2}^-)$	$1P$	2627	2628.1(6)	5942	
$0(\frac{3}{2}^-)$	$2P$	3005		6333	
$0(\frac{3}{2}^-)$	$3P$	3322		6651	
$0(\frac{3}{2}^-)$	$4P$	3606		6922	
$0(\frac{3}{2}^-)$	$5P$	3869		7171	
$0(\frac{3}{2}^+)$	$1D$	2874		6190	
$0(\frac{3}{2}^+)$	$2D$	3189		6526	
$0(\frac{3}{2}^+)$	$3D$	3480		6811	
$0(\frac{3}{2}^+)$	$4D$	3747		7060	
$0(\frac{5}{2}^+)$	$1D$	2880	2881.53(35)	6196	
$0(\frac{5}{2}^+)$	$2D$	3209		6531	
$0(\frac{5}{2}^+)$	$3D$	3500		6814	
$0(\frac{5}{2}^+)$	$4D$	3767		7063	
$0(\frac{5}{2}^-)$	$1F$	3097		6408	
$0(\frac{5}{2}^-)$	$2F$	3375		6705	
$0(\frac{5}{2}^-)$	$3F$	3646		6964	
$0(\frac{5}{2}^-)$	$4F$	3900		7196	
$0(\frac{7}{2}^-)$	$1F$	3078		6411	
$0(\frac{7}{2}^-)$	$2F$	3393		6708	
$0(\frac{7}{2}^-)$	$3F$	3667		6966	
$0(\frac{7}{2}^-)$	$4F$	3922		7197	
$0(\frac{7}{2}^+)$	$1G$	3270		6598	
$0(\frac{7}{2}^+)$	$2G$	3546		6867	
$0(\frac{9}{2}^+)$	$1G$	3284		6599	
$0(\frac{9}{2}^+)$	$2G$	3564		6868	
$0(\frac{9}{2}^-)$	$1H$	3444		6767	
$0(\frac{11}{2}^-)$	$1H$	3460		6766	

arXiv: 1105.0583

TABLE III: Masses of the Σ_Q $(Q = c, b)$ heavy baryons (in MeV).

		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	M^{exp} [1]	M	M^{exp} [1]
$1(\frac{1}{2}^+)$	$1S$	2443	2453.76(18)	5808	5807.8(2.7)
$1(\frac{1}{2}^+)$	$2S$	2901		6213	
$1(\frac{1}{2}^+)$	$3S$	3271		6575	
$1(\frac{1}{2}^+)$	$4S$	3581		6869	
$1(\frac{1}{2}^+)$	$5S$	3861		7124	
$1(\frac{3}{2}^+)$	$1S$	2519	2518.0(5)	5834	5829.0(3.4)
$1(\frac{3}{2}^+)$	$2S$	2936	$2939.3(^{1.4}_{1.5})$?	6226	
$1(\frac{3}{2}^+)$	$3S$	3293		6583	
$1(\frac{3}{2}^+)$	$4S$	3598		6876	
$1(\frac{3}{2}^+)$	$5S$	3873		7129	
$1(\frac{1}{2}^-)$	$1P$	2799	$2802(^{4}_{7})$	6101	
$1(\frac{1}{2}^-)$	$2P$	3172		6440	
$1(\frac{1}{2}^-)$	$3P$	3488		6756	
$1(\frac{1}{2}^-)$	$4P$	3770		7024	
$1(\frac{1}{2}^-)$	$1P$	2713		6095	
$1(\frac{1}{2}^-)$	$2P$	3125		6430	
$1(\frac{1}{2}^-)$	$3P$	3455		6742	
$1(\frac{1}{2}^-)$	$4P$	3743		7008	
$1(\frac{3}{2}^-)$	$1P$	2798	$2802(^{4}_{7})$	6096	
$1(\frac{3}{2}^-)$	$2P$	3172		6430	
$1(\frac{3}{2}^-)$	$3P$	3486		6742	
$1(\frac{3}{2}^-)$	$4P$	3768		7009	
$1(\frac{3}{2}^-)$	$1P$	2773	2766.6(2.4)?	6087	
$1(\frac{3}{2}^-)$	$2P$	3151		6423	
$1(\frac{3}{2}^-)$	$3P$	3469		6736	
$1(\frac{3}{2}^-)$	$4P$	3753		7003	
$1(\frac{5}{2}^-)$	$1P$	2789		6084	
$1(\frac{5}{2}^-)$	$2P$	3161		6421	
$1(\frac{5}{2}^-)$	$3P$	3475		6732	
$1(\frac{5}{2}^-)$	$4P$	3757		6999	
$1(\frac{1}{2}^+)$	$1D$	3041		6311	
$1(\frac{1}{2}^+)$	$2D$	3370		6636	
$1(\frac{3}{2}^+)$	$1D$	3043		6326	
$1(\frac{3}{2}^+)$	$2D$	3366		6647	
$1(\frac{3}{2}^+)$	$1D$	3040		6285	
$1(\frac{3}{2}^+)$	$2D$	3364		6612	
$1(\frac{5}{2}^+)$	$1D$	3038		6284	
$1(\frac{5}{2}^+)$	$2D$	3365		6612	
$1(\frac{5}{2}^+)$	$1D$	3023		6270	
$1(\frac{5}{2}^+)$	$2D$	3349		6598	
$1(\frac{7}{2}^+)$	$1D$	3013		6260	
$1(\frac{7}{2}^+)$	$2D$	3342		6590	
$1(\frac{3}{2}^-)$	$1F$	3288		6550	
$1(\frac{5}{2}^-)$	$1F$	3283		6564	
$1(\frac{5}{2}^-)$	$1F$	3254		6501	
$1(\frac{7}{2}^-)$	$1F$	3253		6500	
$1(\frac{7}{2}^-)$	$1F$	3227		6472	
$1(\frac{9}{2}^-)$	$1F$	3209		6459	
$1(\frac{5}{2}^+)$	$1G$	3495		6749	
$1(\frac{7}{2}^+)$	$1G$	3483		6761	
$1(\frac{7}{2}^+)$	$1G$	3444		6688	
$1(\frac{9}{2}^+)$	$1G$	3442		6687	
$1(\frac{9}{2}^+)$	$1G$	3410		6648	
$1(\frac{11}{2}^+)$	$1G$	3386		6635	

Charmed/bottom baryons

38 states

Ξ_c

TABLE IV: Masses of the Ξ_Q $(Q = c, b)$ heavy baryons with the scalar diquark (in MeV).

		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	$M^{\rm exp}$ [1]	M	$M^{\rm exp}$ [1]
$\frac{1}{2}(\frac{1}{2}^+)$	$1S$	2476	$2470.88(^{34}_{80})$	5803	5790.5(2.7)
$\frac{1}{2}(\frac{1}{2}^+)$	$2S$	2959		6266	
$\frac{1}{2}(\frac{1}{2}^+)$	$3S$	3323		6601	
$\frac{1}{2}(\frac{1}{2}^+)$	$4S$	3632		6913	
$\frac{1}{2}(\frac{1}{2}^+)$	$5S$	3909		7165	
$\frac{1}{2}(\frac{1}{2}^+)$	$6S$	4166		7415	
$\frac{1}{2}(\frac{1}{2}^-)$	$1P$	2792	2791.8(3.3)	6120	
$\frac{1}{2}(\frac{1}{2}^-)$	$2P$	3179		6496	
$\frac{1}{2}(\frac{1}{2}^-)$	$3P$	3500		6805	
$\frac{1}{2}(\frac{1}{2}^-)$	$4P$	3785		7068	
$\frac{1}{2}(\frac{1}{2}^-)$	$5P$	4048		7302	
$\frac{1}{2}(\frac{3}{2}^-)$	$1P$	2819	2819.6(1.2)	6130	
$\frac{1}{2}(\frac{3}{2}^-)$	$2P$	3201		6502	
$\frac{1}{2}(\frac{3}{2}^-)$	$3P$	3519		6810	
$\frac{1}{2}(\frac{3}{2}^-)$	$4P$	3804		7073	
$\frac{1}{2}(\frac{3}{2}^-)$	$5P$	4066		7306	
$\frac{1}{2}(\frac{3}{2}^+)$	$1D$	3059	3054.2(1.3)	6366	
$\frac{1}{2}(\frac{3}{2}^+)$	$2D$	3388		6690	
$\frac{1}{2}(\frac{3}{2}^+)$	$3D$	3678		6966	
$\frac{1}{2}(\frac{3}{2}^+)$	$4D$	3945		7208	
$\frac{1}{2}(\frac{5}{2}^+)$	$1D$	3076	3079.9(1.4)	6373	
$\frac{1}{2}(\frac{5}{2}^+)$	$2D$	3407		6696	
$\frac{1}{2}(\frac{5}{2}^+)$	$3D$	3699		6970	
$\frac{1}{2}(\frac{5}{2}^+)$	$4D$	3965		7212	
$\frac{1}{2}(\frac{5}{2}^-)$	$1F$	3278		6577	
$\frac{1}{2}(\frac{5}{2}^-)$	$2F$	3575		6863	
$\frac{1}{2}(\frac{5}{2}^-)$	$3F$	3845		7114	
$\frac{1}{2}(\frac{5}{2}^-)$	$4F$	4098		7339	
$\frac{1}{2}(\frac{7}{2}^-)$	$1F$	3292		6581	
$\frac{1}{2}(\frac{7}{2}^-)$	$2F$	3592		6867	
$\frac{1}{2}(\frac{7}{2}^-)$	$3F$	3865		7117	
$\frac{1}{2}(\frac{7}{2}^-)$	$4F$	4120		7342	
$\frac{1}{2}(\frac{7}{2}^+)$	$1G$	3469		6760	
$\frac{1}{2}(\frac{7}{2}^+)$	$2G$	3745		7020	
$\frac{1}{2}(\frac{9}{2}^+)$	$1G$	3483		6762	
$\frac{1}{2}(\frac{9}{2}^+)$	$2G$	3763		7032	
$\frac{1}{2}(\frac{9}{2}^-)$	$1H$	3643		6933	
$\frac{1}{2}(\frac{11}{2}^-)$	$1H$	3658		6934	

Ξ_c

54 states

TABLE V: Masses of the Ξ_Q $(Q = c, b)$ heavy baryons with the axial vector diquark (in MeV).

		$Q = c$		$Q = b$
$I(J^P)$	Qd state	M	$M^{\rm exp}$ [1]	M
$\frac{1}{2}(\frac{1}{2}^+)$	$1S$	2579	2577.9(2.9)	5936
$\frac{1}{2}(\frac{1}{2}^+)$	$2S$	2983	2971.4(3.3)	6329
$\frac{1}{2}(\frac{1}{2}^+)$	$3S$	3377		6687
$\frac{1}{2}(\frac{1}{2}^+)$	$4S$	3695		6978
$\frac{1}{2}(\frac{1}{2}^+)$	$5S$	3978		7229
$\frac{1}{2}(\frac{3}{2}^+)$	$1S$	2649	2645.9(0.5)	5963
$\frac{1}{2}(\frac{3}{2}^+)$	$2S$	3026		6342
$\frac{1}{2}(\frac{3}{2}^+)$	$3S$	3396		6695
$\frac{1}{2}(\frac{3}{2}^+)$	$4S$	3709		6984
$\frac{1}{2}(\frac{3}{2}^+)$	$5S$	3989		7234
$\frac{1}{2}(\frac{1}{2}^-)$	$1P$	2936	2931(6)	6233
$\frac{1}{2}(\frac{1}{2}^-)$	$2P$	3313		6611
$\frac{1}{2}(\frac{1}{2}^-)$	$3P$	3630		6915
$\frac{1}{2}(\frac{1}{2}^-)$	$4P$	3912		7174
$\frac{1}{2}(\frac{1}{2}^-)$	$1P$	2854		6227
$\frac{1}{2}(\frac{1}{2}^-)$	$2P$	3267		6604
$\frac{1}{2}(\frac{1}{2}^-)$	$3P$	3598		6906
$\frac{1}{2}(\frac{1}{2}^-)$	$4P$	3887		7164
$\frac{1}{2}(\frac{3}{2}^-)$	$1P$	2935	2931(6)	6234
$\frac{1}{2}(\frac{3}{2}^-)$	$2P$	3311		6605
$\frac{1}{2}(\frac{3}{2}^-)$	$3P$	3628		6905
$\frac{1}{2}(\frac{3}{2}^-)$	$4P$	3911		7163
$\frac{1}{2}(\frac{3}{2}^-)$	$1P$	2912		6224
$\frac{1}{2}(\frac{3}{2}^-)$	$2P$	3293		6598
$\frac{1}{2}(\frac{3}{2}^-)$	$3P$	3613		6900
$\frac{1}{2}(\frac{3}{2}^-)$	$4P$	3898		7159
$\frac{1}{2}(\frac{5}{2}^-)$	$1P$	2929	2931(6)	6226
$\frac{1}{2}(\frac{5}{2}^-)$	$2P$	3303		6596
$\frac{1}{2}(\frac{5}{2}^-)$	$3P$	3619		6897
$\frac{1}{2}(\frac{5}{2}^-)$	$4P$	3902		7156
$\frac{1}{2}(\frac{1}{2}^+)$	$1D$	3163		6447
$\frac{1}{2}(\frac{1}{2}^+)$	$2D$	3505		6767
$\frac{1}{2}(\frac{3}{2}^+)$	$1D$	3167		6459
$\frac{1}{2}(\frac{3}{2}^+)$	$2D$	3506		6775
$\frac{1}{2}(\frac{3}{2}^+)$	$1D$	3160		6431
$\frac{1}{2}(\frac{3}{2}^+)$	$2D$	3497		6751
$\frac{1}{2}(\frac{5}{2}^+)$	$1D$	3166		6432
$\frac{1}{2}(\frac{5}{2}^+)$	$2D$	3504		6751
$\frac{1}{2}(\frac{5}{2}^+)$	$1D$	3153		6420
$\frac{1}{2}(\frac{5}{2}^+)$	$2D$	3493		6740
$\frac{1}{2}(\frac{7}{2}^+)$	$1D$	3147	3122.9(1.3)	6414
$\frac{1}{2}(\frac{7}{2}^+)$	$2D$	3486		6736
$\frac{1}{2}(\frac{3}{2}^-)$	$1F$	3418		6675
$\frac{1}{2}(\frac{5}{2}^-)$	$1F$	3408		6686
$\frac{1}{2}(\frac{5}{2}^-)$	$1F$	3394		6640
$\frac{1}{2}(\frac{7}{2}^-)$	$1F$	3393		6641
$\frac{1}{2}(\frac{7}{2}^-)$	$1F$	3373		6619
$\frac{1}{2}(\frac{9}{2}^-)$	$1F$	3357		6610
$\frac{1}{2}(\frac{5}{2}^+)$	$1G$	3623		6867
$\frac{1}{2}(\frac{7}{2}^+)$	$1G$	3608		6876
$\frac{1}{2}(\frac{7}{2}^+)$	$1G$	3584		6822
$\frac{1}{2}(\frac{9}{2}^+)$	$1G$	3582		6821
$\frac{1}{2}(\frac{9}{2}^+)$	$1G$	3558		6792
$\frac{1}{2}(\frac{11}{2}^+)$	$1G$	3536		6782

arXiv: 1105.0583

Charmed/bottom baryons

54 states

Ω_c

TABLE VI: Masses of the Ω_Q ($Q = c, b$) heavy baryons (in MeV).

$I(J^P)$	Qd state	$Q=c$ M	$Q=c$ $M^{\rm exp}$ [1]	$Q=b$ M	$Q=b$ $M^{\rm exp}$ [1]
$0(\frac{1}{2}^+)$	$1S$	2698	2695.2(1.7)	6064	6071(40)
$0(\frac{1}{2}^+)$	$2S$	3088		6450	
$0(\frac{1}{2}^+)$	$3S$	3489		6804	
$0(\frac{1}{2}^+)$	$4S$	3814		7091	
$0(\frac{1}{2}^+)$	$5S$	4102		7338	
$0(\frac{3}{2}^+)$	$1S$	2768	2765.9(2.0)	6088	
$0(\frac{3}{2}^+)$	$2S$	3123		6461	
$0(\frac{3}{2}^+)$	$3S$	3510		6811	
$0(\frac{3}{2}^+)$	$4S$	3830		7096	
$0(\frac{3}{2}^+)$	$5S$	4114		7343	
$0(\frac{1}{2}^-)$	$1P$	3055		6339	
$0(\frac{1}{2}^-)$	$2P$	3435		6710	
$0(\frac{1}{2}^-)$	$3P$	3754		7009	
$0(\frac{1}{2}^-)$	$4P$	4037		7265	
$0(\frac{1}{2}^-)$	$1P$	2966		6330	
$0(\frac{1}{2}^-)$	$2P$	3384		6706	
$0(\frac{1}{2}^-)$	$3P$	3717		7003	
$0(\frac{1}{2}^-)$	$2P$	4009		7257	
$0(\frac{3}{2}^-)$	$1P$	3054		6340	
$0(\frac{3}{2}^-)$	$2P$	3433		6705	
$0(\frac{3}{2}^-)$	$3P$	3752		7002	

TABLE VI: (continued)

$I(J^P)$	Qd state	$Q=c$ M	$Q=c$ $M^{\rm exp}$ [1]	$Q=b$ M	$Q=b$ $M^{\rm exp}$ [1]
$0(\frac{3}{2}^-)$	$4P$	4036		7258	
$0(\frac{3}{2}^-)$	$1P$	3029		6331	
$0(\frac{3}{2}^-)$	$2P$	3415		6699	
$0(\frac{3}{2}^-)$	$3P$	3737		6998	
$0(\frac{3}{2}^-)$	$4P$	4023		7250	
$0(\frac{5}{2}^-)$	$1P$	3051		6334	
$0(\frac{5}{2}^-)$	$2P$	3427		6700	
$0(\frac{5}{2}^-)$	$3P$	3744		6996	
$0(\frac{5}{2}^-)$	$4P$	4028		7251	
$0(\frac{1}{2}^+)$	$1D$	3287		6540	
$0(\frac{1}{2}^+)$	$2D$	3623		6857	
$0(\frac{3}{2}^+)$	$1D$	3298		6549	
$0(\frac{3}{2}^+)$	$2D$	3627		6863	
$0(\frac{3}{2}^+)$	$1D$	3282		6530	
$0(\frac{3}{2}^+)$	$2D$	3613		6846	
$0(\frac{5}{2}^+)$	$1D$	3297		6529	
$0(\frac{5}{2}^+)$	$2D$	3626		6846	
$0(\frac{5}{2}^+)$	$1D$	3286		6520	
$0(\frac{5}{2}^+)$	$2D$	3614		6837	
$0(\frac{7}{2}^+)$	$1D$	3283		6517	
$0(\frac{7}{2}^+)$	$2D$	3611		6834	
$0(\frac{3}{2}^-)$	$1F$	3533		6763	
$0(\frac{5}{2}^-)$	$1F$	3522		6771	
$0(\frac{5}{2}^-)$	$1F$	3515		6737	
$0(\frac{7}{2}^-)$	$1F$	3514		6736	
$0(\frac{7}{2}^-)$	$1F$	3498		6719	
$0(\frac{9}{2}^-)$	$1F$	3485		6713	
$0(\frac{5}{2}^+)$	$1G$	3739		6952	
$0(\frac{7}{2}^+)$	$1G$	3721		6959	
$0(\frac{7}{2}^+)$	$1G$	3707		6916	
$0(\frac{9}{2}^+)$	$1G$	3705		6915	
$0(\frac{9}{2}^+)$	$1G$	3685		6892	
$0(\frac{11}{2}^+)$	$1G$	3665		6884	

arXiv: 1105.0583