Theories for quarkonia production (mainly pp and pA)

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Outline

I. Introduction

II. Theories for quarkonia in pp

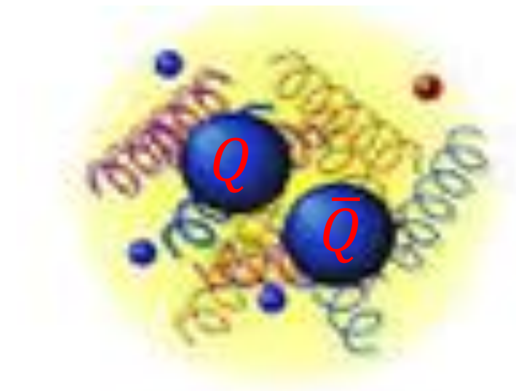
III. Theories for quarkonia in pA

IV. Summary and outlook

Heavy quarkonia

- Bound state of $Q\bar{Q}$ pair under strong interaction
  - The simplest system in QCD: two-body problem
  - Virial theorem + uncertainty principle:

    $mv^2 \sim V(r) \sim r^{-1}\alpha_s(1/r) \;\&\; r \sim (mv)^{-1} \Rightarrow \alpha_s(mv) \sim v$



- Non-relativistic system: $v^2 \ll 1$
  - Charmonium: $m \sim 1.3\text{GeV}, \; v^2 \approx 0.3$
  - Bottomonium: $m \sim 4.5\text{GeV}, \; v^2 \approx 0.1$
- Multiple well-separated scales :

Quark mass:	m	
Momentum:	mv	$m \gg mv \gg mv^2 \sim \Lambda_{QCD}$
Energy:	mv^2	

- Involving both pert. and nonpert. physics

Production of heavy quarkonia

- **pp: study hadronization mechanism**
  - Quarkonium production can be traced by heavy quark pair (vs light hadron), unique to explore hadronization mechanism
  - Production mechanism?
- **pA: study Cold Nuclear Matter effect**
  - Initial state: nPDF, energy loss, saturation CGC
  - Final state: nuclear absorption, comovers
  - Need pp as input
- **AA: study QGP**
  - Dissociation, suppression, recombination
  - Need pp&pA as input

Theories for extreme p_T

➢ High $p_T \gg m$: CO factorization

Kang, Qiu, Sterman, 1109.1520
Kang, YQM, Qiu, Sterman, 1401.0923

- Power expansion, double parton fragmentation
- Resummation of large log $\ln(p_T/m)$

➢ Low $p_T \ll m$: k_T-dependent factorization

YQM, Venugopalan, 1408.4075
Watanabe, Xiao, 1507.06564

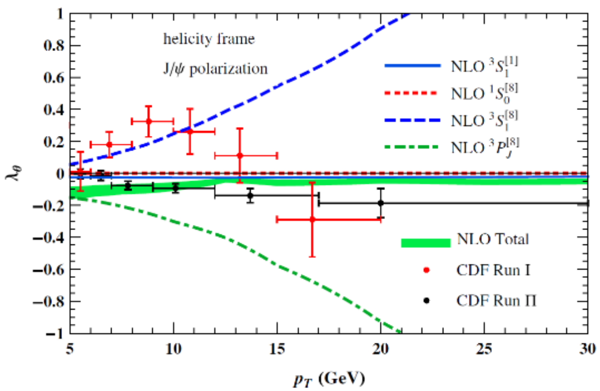
- Resum Sudakov log $\ln(p_T/m)$
- Color Glass Condensate: resum small-x log $\ln(x)$, higher twist contributions

Theories for $p_T \sim m$

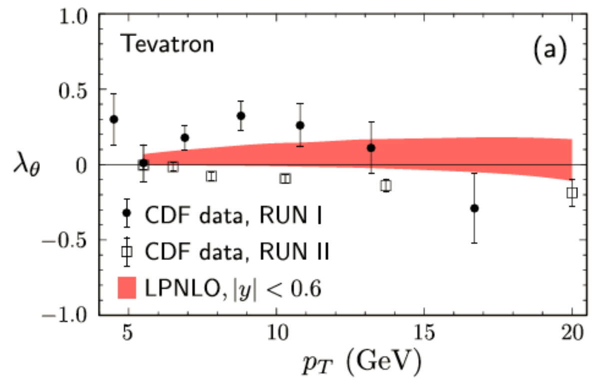
- **Color Singlet Model** Einhorn, Ellis (1975), Chang (1980) …
  - ✓ Simple enough, no free parameter
  - × Over simplified: IR div., cannot derived from QCD with proper approx.
  - × Pheno: ψ' surplus, …
- **Color Evaporation Model** Fritzsch (1977), Halzen (1977) …
  - ✓ Simple enough, one parameter for each quarkonium
  - ✓ Factorization expects to hold to all orders!
  - × Over simplified: cannot derived from QCD with proper approx.
  - × Pheno: wrong for ratios, p_T distribution, …
  - Improved-CEM: soft gluon radiation considered, YQM, Vogt, 1609.06042 some pheno problems solved
- **Non-relativistic QCD** Caswell, Lepage, PLB 1986; Bodwin, Braaten, Lepage, 9407339
- **Soft gluon factorization** YQM, Chao, 1703.08402; Chen, YQM, 2005.08786

NRQCD: polarization puzzle

- J/ψ at NLO: transverse polarization largely canceled (***natural?***) between ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$



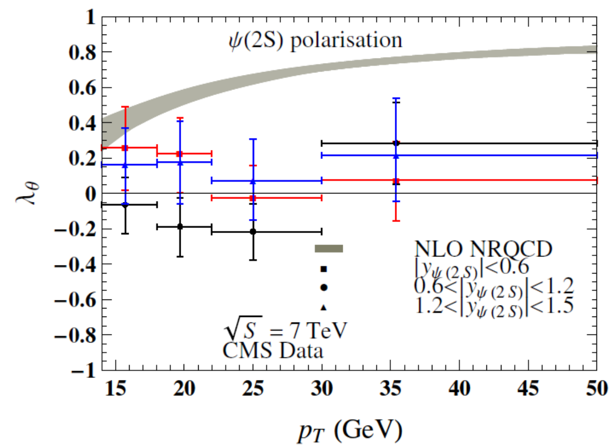
Chao,YQM,Shao,Wang, Zhang,1201.2675



Bodwin, Chung, Kim, Lee, 1403.3612

- $\psi(2S)$ at NLO: cancelation is weak, still hard to understand

Shao, Han, YQM, Meng, Zhang, Chao, 1411.3300



NRQCD: universality problem

- **Necessary condition for NRQCD**
  - LDMEs are process independent
- **Upper bound of M_0 set by e^+e^- collision**

Zhang, YQM, Wang, Chao, 0911.2166

$$M_0 < 0.02\text{GeV}^3$$

  - Comparing with $\mathrm{M}_0 \approx 0.074$ GeV^3 from pp collison
- **Global fit of LDMEs**

Butenschoen, Kniehl, 1105.0820

$$\chi^2_{\text{d.o.f.}} = 725/194 = 3.74$$

  - Data cannot be described consistently!

Rigorousness of NRQCD factorization

- Likely a rigorous theory
  - Based on EFT of QCD: NRQCD
  - Double expansion of small quantities: α_s, v^2
  - Factorization has been tested to NNLO

Nayak, Qiu, Sterman, 0509021
Bodwin, Chung, Ee, Kim, Lee, 1910.05497

- Why does it not work for quarkonia production?

The problem: convergence of relativistic expansion!

Soft gluon momentum: convergence

- **Soft gluon emission in color-bleaching process**
  - P_ψ is different from P, $P = P_\psi[1 + O(\lambda)]$
  - NRQCD approximates P by P_ψ

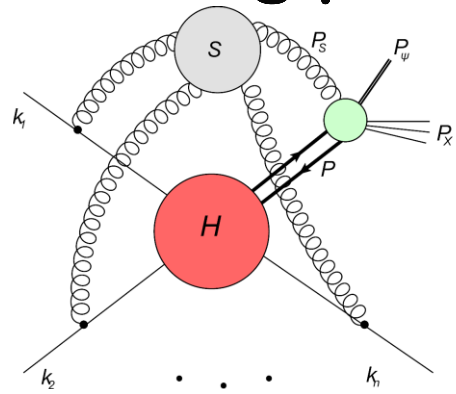


Fig from: YQM, Vogt, 1609.06042

- **An over simplified model of NRQCD expansion**
  - Cross section approximately $\propto P^{-4} = P_\psi^{-4}[1 + O(\lambda)]^{-4}$

$$\int_{-1}^{1} \frac{d\cos\theta}{2(1+\lambda+\lambda\cos\theta)^4} = 0.42$$

With $\lambda \approx v^2 \approx 0.3$

$$= 1 - 4\lambda + 40/3\lambda^2 - 40\lambda^3 + \cdots$$

$$= 1 - 1.2 + 1.2 - 1.08 + 0.91 - 0.73 + \cdots$$

Mangano, Petrelli, 9610364

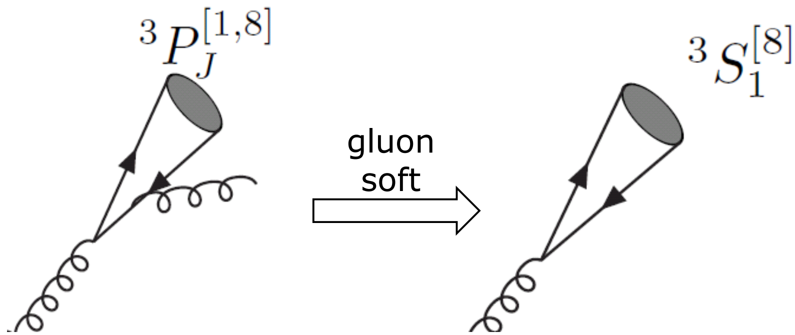
An effect known long time ago, but without a proper treatment

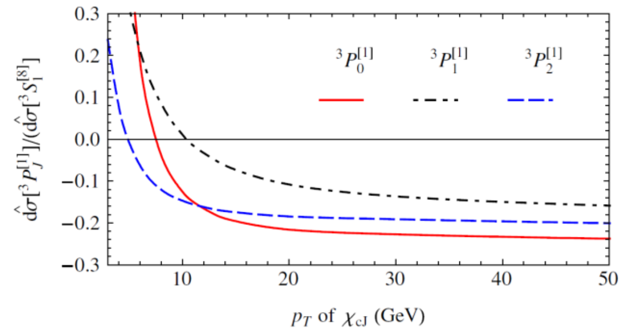
Soft gluon momentum: over subtraction

- Eg. χ_{cJ} production:

YQM, Wang, Chao, 1002.3987
Braaten, Chen, 9610401

$$d\sigma_{\chi_{cJ}}/(2J+1) \approx d\hat{\sigma}_{^3P_J^{[1]}} \langle O\left(^3P_0^{[1]}\right)\rangle + d\hat{\sigma}_{^3S_1^{[8]}} \langle O\left(^3S_1^{[8]}\right)\rangle$$





- Soft gluon in P-wave: factorized to S-wave matrix element
- Subtraction scheme: at *zero momentum*, which contributes the largest production rate. Over subtracted! P-wave negative!
- Big cancellation between S-wave and P-wave! Perturbation unstable
- To solve it, soft gluon momentum should be kept in subtraction

- Similar to the over subtraction problem in single hadron production in pA collision

Chirilli, Xiao, Yuan, 1112.1061;
Stasto, Xiao, Zaslavsky, 1307.4057;
Liu, YQM, Chao, 1909.02370;
Liu, Kang, Liu, 2004.11990

Soft gluon factorization (SGF)

YQM, Chao, 1703.08402

➢ SGF for quarkonium H production:

$$(2\pi)^3 2P_H^0 \frac{d\sigma_H}{d^3P_H} \approx \sum_n \int \frac{d^4P}{(2\pi)^4} \mathcal{H}_n(P) F_{n\to H}(P, P_H)$$

- $n = {}^{2S+1}L_J^{[c]}$
- P: momentum of $Q\bar{Q}$
- $\mathcal{H}_n$: perturbatively calculable hard parts
- $F_{n\to H}$: nonperturbabtive soft gluon distributions (SGDs)
- UV renormalization scale is suppressed

➢ Keep momentum difference between $Q\bar{Q}$ and H

- Expect no further large relativistic corrections

➢ Set $P \approx P_H$ in hard part: "reproduce" NRQCD

$$(2\pi)^3 2P_H^0 \frac{d\sigma_H}{d^3P_H} \approx \sum_n \mathcal{H}_n(P_H) \langle \widetilde{\mathcal{O}}_n^H \rangle$$

$$\langle \widetilde{\mathcal{O}}_n^H \rangle = \int \frac{d^4P}{(2\pi)^4} F_{n\to H}(P, P_H)$$

From NRQCD EFT to SGF

Equation of motion used in NRQCD

Chen, YQM, 2005.08786

$$\left(iD_0 - \frac{\boldsymbol{D}^2}{2m} + \cdots\right)\psi = 0$$

- If ignoring gluon field, replace D by ∇
- In NRQCD, use EOM to remove ∇_0. Then for heavy quark pair, $\vec{\nabla}$ decomposed to relative derivative and total derivative
- Beginning from $\chi^\dagger\psi$, one can construct $\chi^\dagger \overleftrightarrow{\boldsymbol{\nabla}}^2\psi$ and $\boldsymbol{\nabla}^2(\chi^\dagger\psi)$

The strategy in SGF

- EOM can be used to remove relative derivatives, leaving only total derivatives (again two degrees of freedom)

$$\langle \mathcal{Q} + X | \nabla_0^{n_1} \boldsymbol{\nabla}^{2n_2} (\psi^\dagger \chi) | 0 \rangle$$

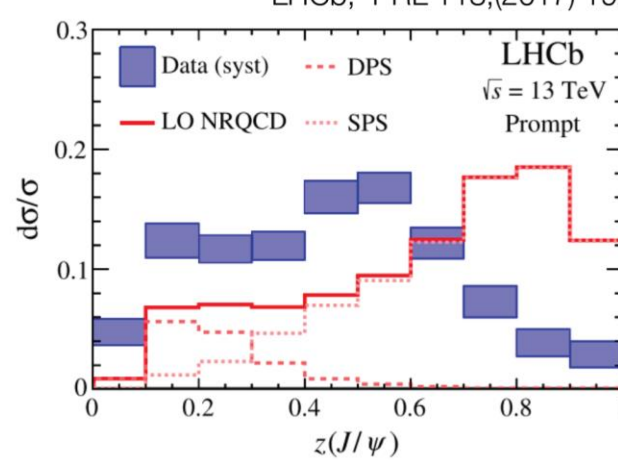
- Integration by parts remove operators except $n_1 = n_2 = 0$
- Matching coefficients are functions of $P_X^2, P_X \cdot P, P^2$
- SGF obtained, kinematic effects in NRQCD resummed
- SGF is a generalization of NRQCD factorization

Summary for pp

- Theories based on QCD
  - NRQCD factorization: rigorous but bad convergence
  - SGF: rigorous, a subset of v^2 correction resummed, good convergence expected
  - Open question: prove factorization to all orders!
- Large logs rigorously resummed

An era to fully understand production mechanism!

LHCb, PRL 118,(2017) 192001



- E.g., J/ψ production in jets: problem likely solvable in SGF   See Q. Yang talk (Tue: D2)
- Stay tuned!

Difference between pp and pA

- **Different for initial state parton distribution (modify CO factorization)**
  - Modification of PDF in nuclei: still CO fac., with nPDF
  - Gluon saturation (similar physics may appear in pp): use CGC fac., multiparton interaction resummed, small-x log resummed
  - Parton propagation in medium: energy loss, convolution factor
- **Different for final state interaction (modify quarkonium factorization)**
  - Break up in the nuclear matter: nuclear absorption
  - Break up by commoving particles: comover interaction (not completely different, comovers also exist in pp, can be more important in pA)

Initial state: leading twist or higher twist?

➢ Depends on gluon density

- Nucleus has $A^{1/3}$ times more gluons
- More gluons at small-x (especially forward production region): gluon splitting from DGLAP evolution
- Saturated gluons has occupation numbers $O(1/\alpha_s)$, with typical momenta at the order of saturation scale $k_T \sim Q_s$: higher twist no α_s suppression

➢ Depends on scales

- Higher twist suppressed by Q_s^2/Q^2
- Q^2 is hard scale, should chosen as $m_T^2 = m^2 + p_T^2$: higher twist contribution is less important for bottomium and high p_T

➢ Charmonium at low p_T may need higher twist

- nPDF: leading twist
- CGC and energy loss: higher twist

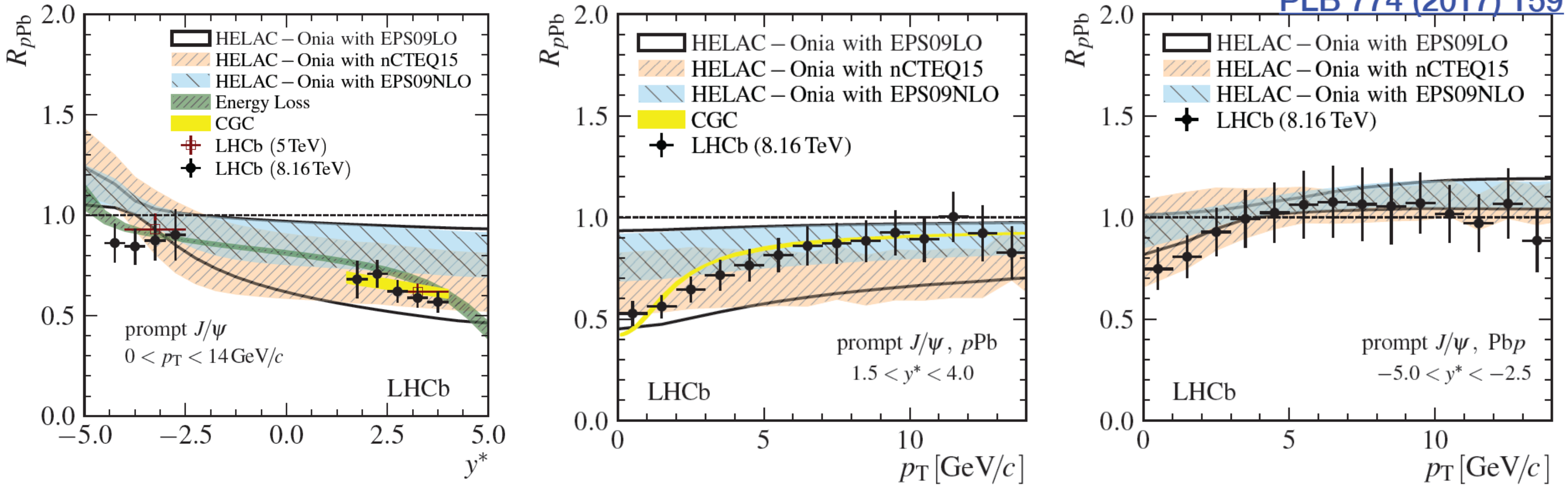
Ground state production in pA

- J/ψ production in pA: evidence of higher twist contribution?

See also O. Boente talk (Tue: D2 LHCb)

Prompt J/ψ

PLB 774 (2017) 159



- All models provide reasonable description within uncertainty
- nPDFs: too large uncertainty, hard to conform or rule out
- CGC gives best description (within the scope of application)
- Open question: how to extend the scope of application of CGC?

Final state: nuclear absorption

➢ Time scales

$$t_t \sim 2R_A \frac{m_n}{E_n},$$
$$t_c \sim \frac{1}{2m}\frac{E}{m} > \frac{1}{2m},$$
$$t_f \sim \frac{1}{mv^2}\frac{E}{m} \sim \frac{t_c}{v^2},$$

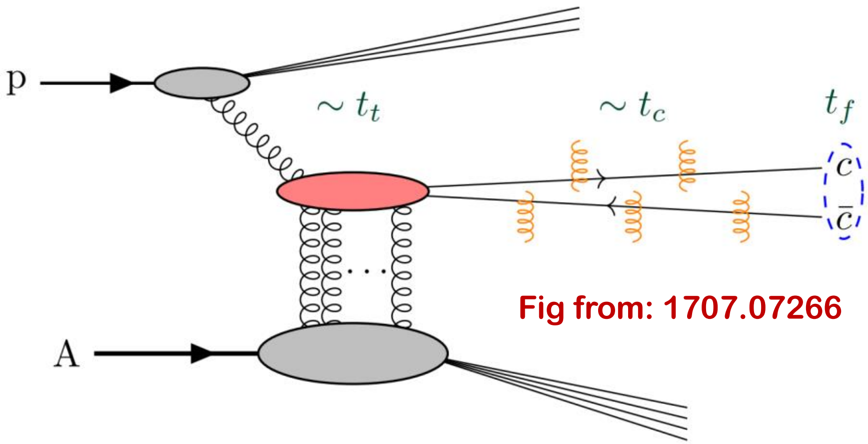


Fig from: 1707.07266

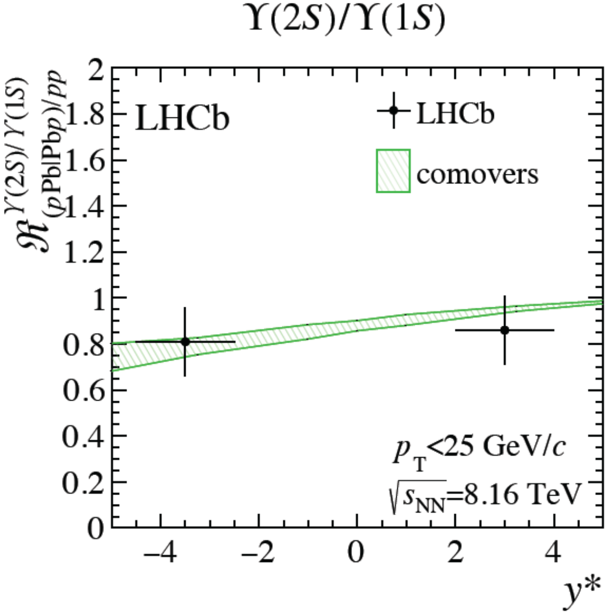
- t_t **time for traverse the nucleus,** ~ 0.05 **fm for PHENIX,** ~ 0.002 **fm for ALICE**
- t_c **time for** $Q\bar{Q}$ **production,** > 0.07 **fm for charm**
- t_f **time for quarkonium formation** ⇨ $t_f \gg t_t$

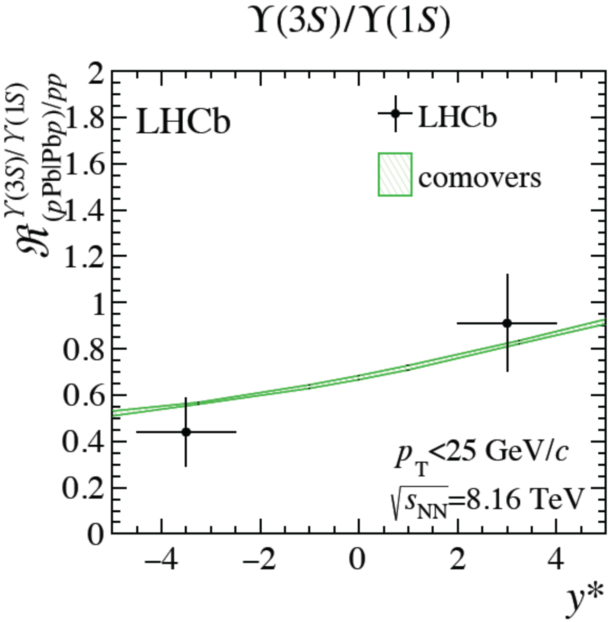
Quarkonium formed outside of nucleus, nuclear absorption is negligible

Final state: comovers

- **Relative suppression of excited states**

See also O. Boente talk (Tue: D2 LHCb)





- Similar initial state information, only final state interaction matters
- Excited states are loosely bounded, easier affected by comovers; evidence of comovers effect?
- Other explanations

Kisslinger, 1412.4747;
Du, Rapp, 1504.00670;
Chen, Guo, Liu, Zhuang, 1607.07927

Hadron comover model

➢ Evolution of quarkonium density

Ferreiro, Lansberg, 1804.04474

$$\tau \frac{d\rho^{\Upsilon}}{d\tau}(b,s,y) = -\sigma^{co-\Upsilon}\rho^{co}(b,s,y)\,\rho^{\Upsilon}(b,s,y)$$

Dissociation Xsec one for each onium → $\sigma^{co-\Upsilon}$

Comover density → ρ^{co}

Quarkonium density → ρ^{Υ}

- Bose-Einstein distribution of comover: effective temperature $T_{\rm eff} \approx 200$MeV

$$\mathcal{P}(E^{co};T_{\rm eff}) \propto 1/(e^{E^{co}/T_{\rm eff}}-1)$$

	CIM	Exp
	$-1.93 < y < 1.93$	CMS data
$\Upsilon(2S)/\Upsilon(1S)$	0.91 ± 0.03	0.83 ± 0.05 (stat.) ± 0.05 (syst.)
$\Upsilon(3S)/\Upsilon(1S)$	0.72 ± 0.02	0.71 ± 0.08 (stat.) ± 0.09 (syst.)
	$-2.0 < y < 1.5$	ATLAS data
$\Upsilon(2S)/\Upsilon(1S)$	0.90 ± 0.03	0.76 ± 0.07 (stat.) ± 0.05 (syst.)
$\Upsilon(3S)/\Upsilon(1S)$	0.71 ± 0.02	0.64 ± 0.14 (stat.) ± 0.06 (syst.)

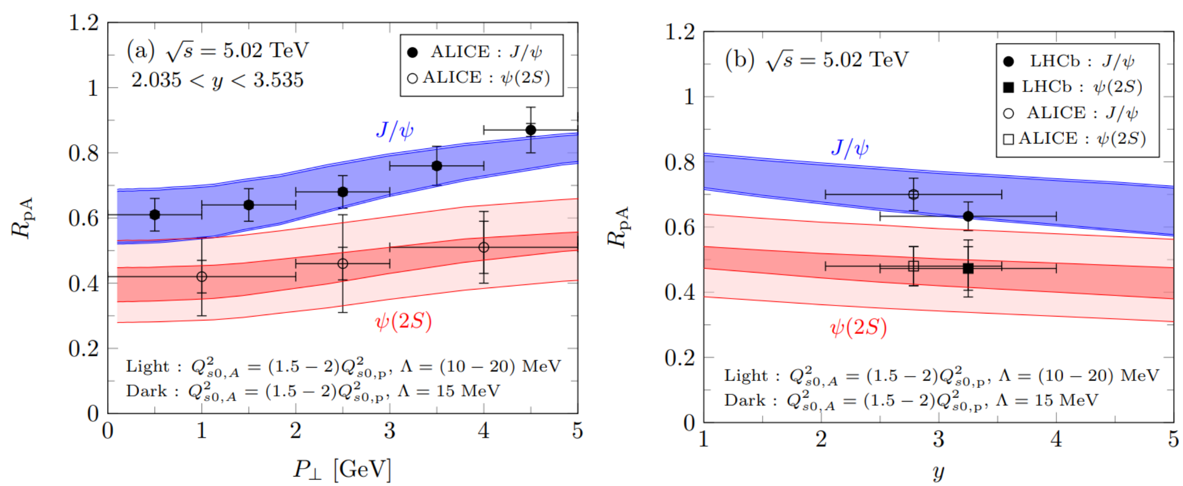
Parton comover model

- **Interaction with comover is dynamic**
  - Not only disassociate quarkonium, but also make it hard to form
  - Factorization broken: hadronization functions (LDMEs in NRQCD, or SGDs in SGF) are not universal, depending on processes
  - Open question: a factorization method to deal with comover?
- **A dynamic model: ICEM with a cutoff**

$$\frac{d\sigma_\psi}{d^2P_\perp dy} = F_\psi \int_{m_\psi}^{2m_D-\Lambda} dM \left(\frac{M}{m_\psi}\right)^2 \frac{d\sigma_{c\bar{c}}}{dM d^2P'_\perp dy}\bigg|_{P'_\perp=\frac{M}{m_\psi}P_\perp}$$

YQM, Venugopalan, Watanabe, Zhang,1707.07266

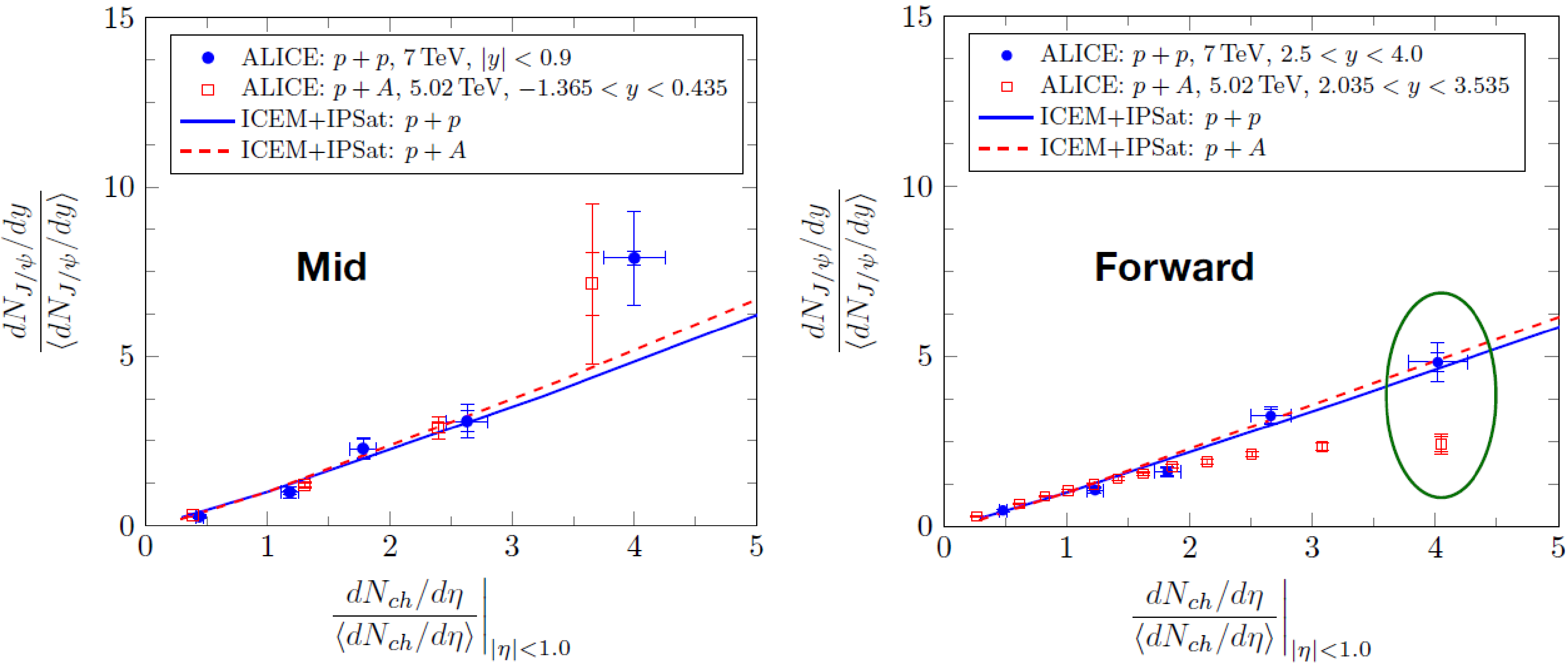
  - Λ: average momentum exchanged from parton comovers



$\Lambda = 10$–20 MeV

Quarkonium with high multiplicity

See K. Watanabe talk (Tue: C3)



The interplay between coherent (initial state) and incoherent (final state) rescattering effects may account for the J/ψ's suppression in p+A collisions at forward rapidity.

Quarkonium in AA

- **Transport coefficients from in medium quarkonium dynamics** See M. Escobedo talk (Mon: B2)
  - The transport parameter κ provides a link between heavy quark diffusion and quarkonium suppression.
  - We have determined κ and γ non-perturbatively using lattice QCD data.
  - More on Effective Field Theories and lattice QCD on Nora Brambilla's plenary talk on Thursday.

- **Coupled Transport Equations for Quarkonium Production in Heavy Ion Collisions** See X. Yao talk (Mon: B2)
  - Recent theoretical developments using open quantum system: wavefunction decoherence —> dissociation, recombination occurs at the same time
  - Construct coupled transport equations of open heavy flavors and quarkonium, can handle correlated and uncorrelated recombination

Summary

- pp: Soft gluon factorization may provide a new hope to fully understand production mechanism
- pA: models for initial state effects have not been distinguished
- pA: a rigorous factorization method for comover is still missing
- Multiplicity in pp, pA, AA; quarkonium dissociation, suppression, recombination in AA under study

Thank you!