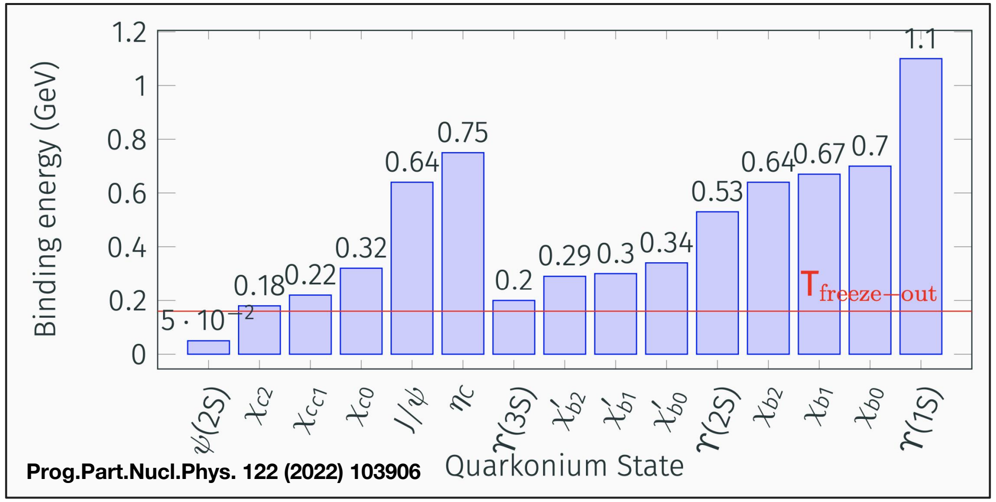
Recent conventional and exotic charmonia results from LHCb

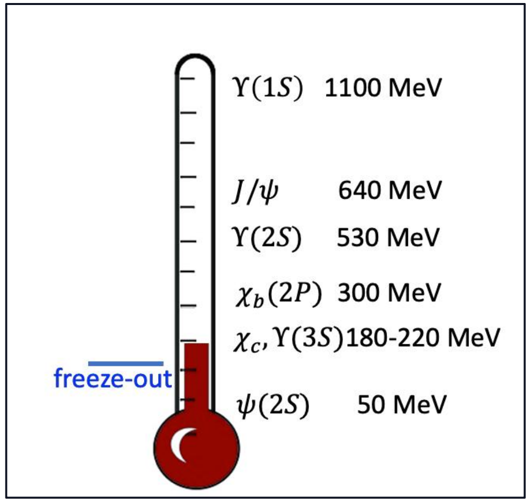
On behalf on LHCb collaboration
Youen Kang
June 4th, 2024

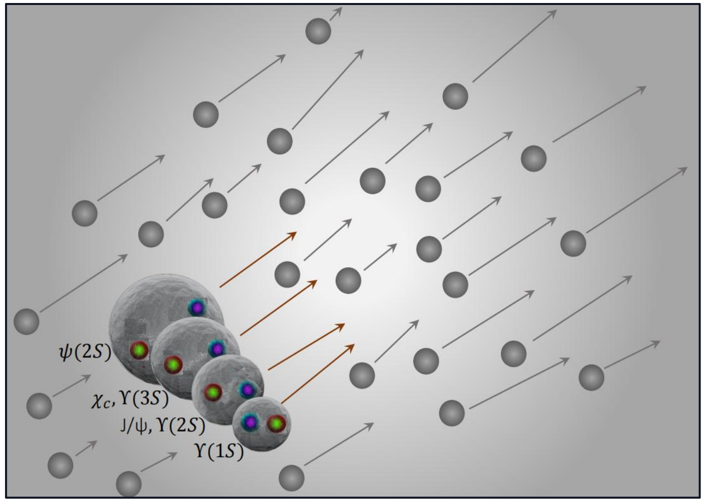
SQM2024

Quarkonium states



Prog.Part.Nucl.Phys. 122 (2022) 103906





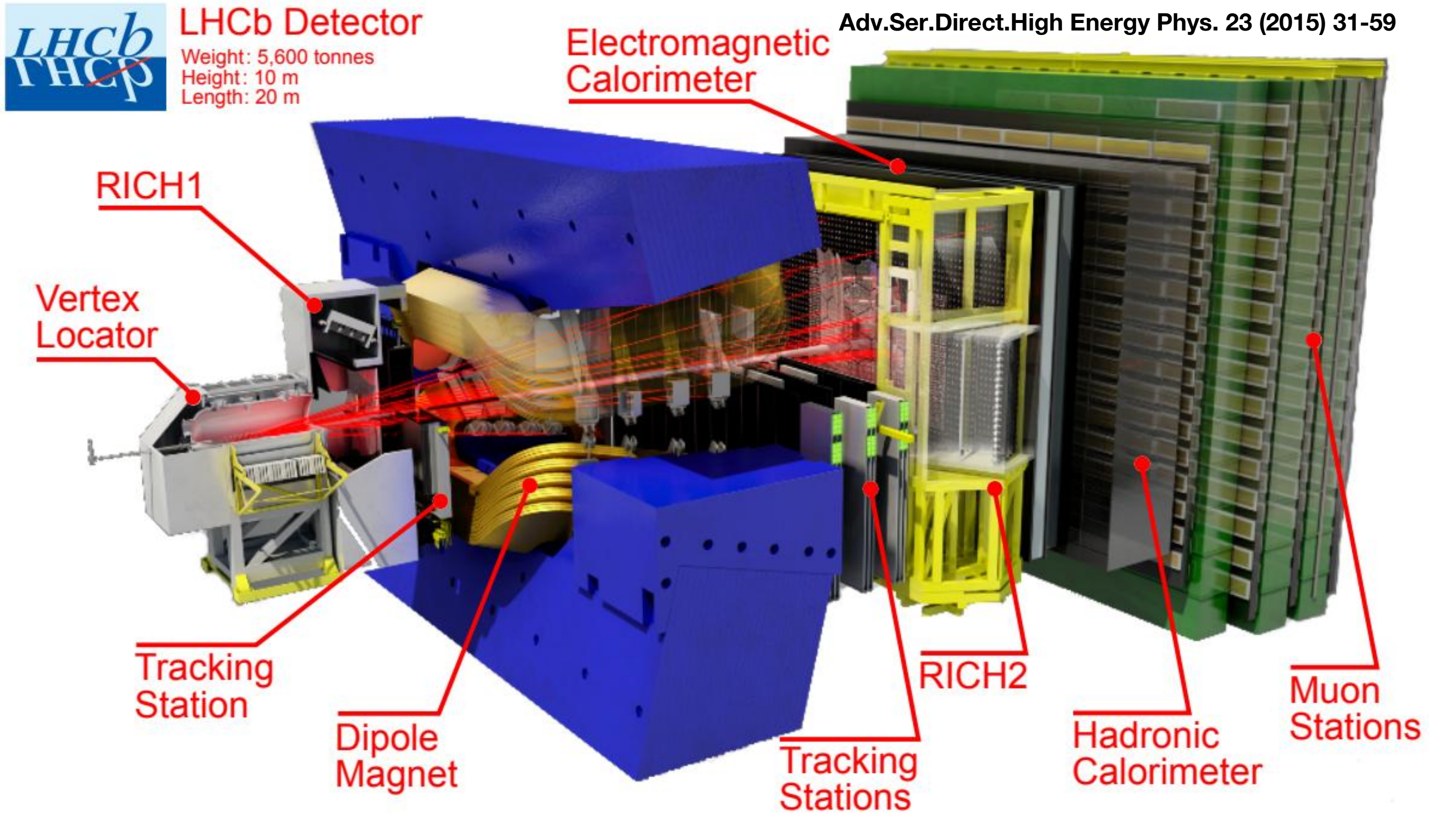
Quarkonium is sensitive to the environment where it is produced:

- ➢ Quarkonium is inhibit to produce when temperature is higher than its binding energy [PRC 99 (2019) 044914]
- ➢ Quarkonium dissociate when interacting with co-moving particles [Ferrero, PLB749, 98 (2015)]

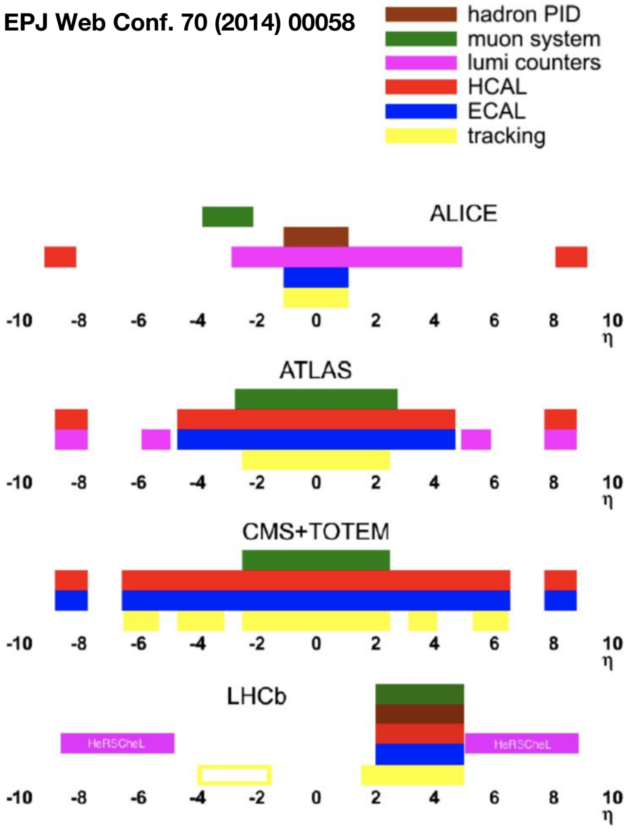
Quarkonium of higher states with larger radius tends to dissociate first.

Excited-to-ground ratio probes for final-state effects (Initial-state effects cancel out).

The LHCb detector



Adv.Ser.Direct.High Energy Phys. 23 (2015) 31-59

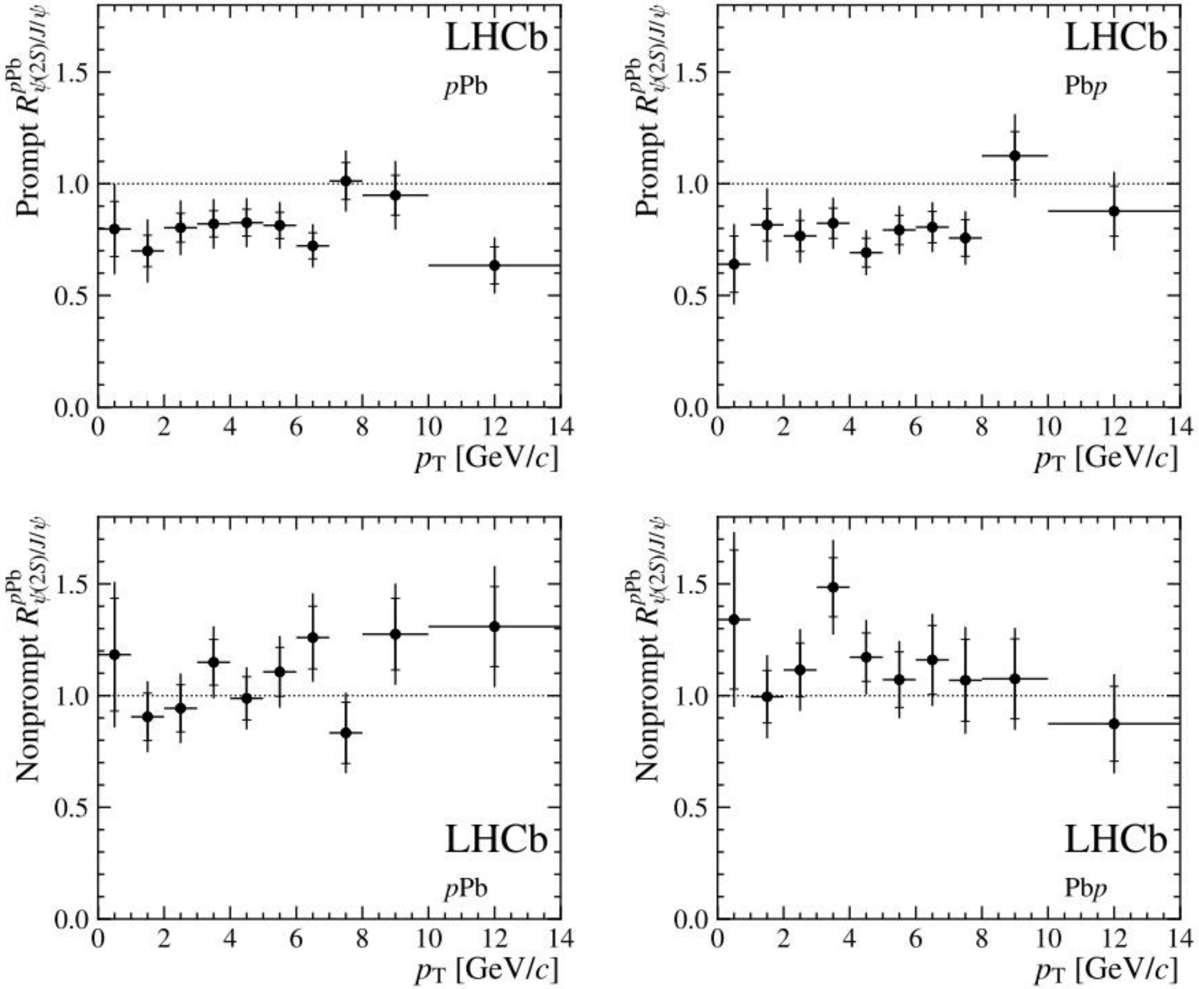


EPJ Web Conf. 70 (2014) 00058

- Optimum detector for quarkonium study
- Unique forward instrumentation for heavy ion physics
- $e, \mu, \pi, K, p, \gamma$ jet identification in $1<p<100$ GeV/c

$\psi(2S)$-to-J/ψ double ratio at $\sqrt{s_{NN}} = 8.16$ TeV

$$R^{p\mathrm{Pb}}_{\psi(2S)/J/\psi} = \frac{R_{p\mathrm{Pb}}(\psi(2S))}{R_{p\mathrm{Pb}}(J/\psi)} = \frac{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{p\mathrm{Pb}}}{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{pp}}$$



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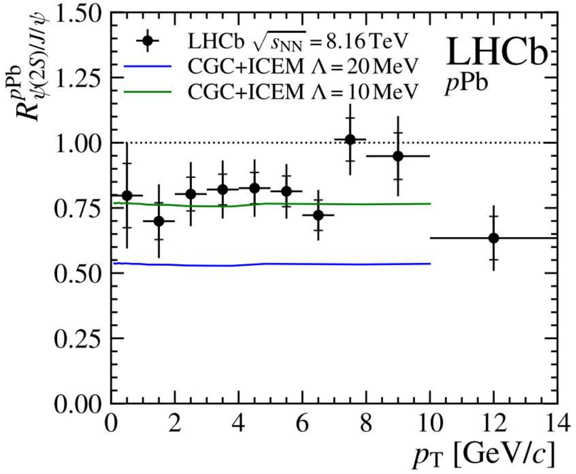
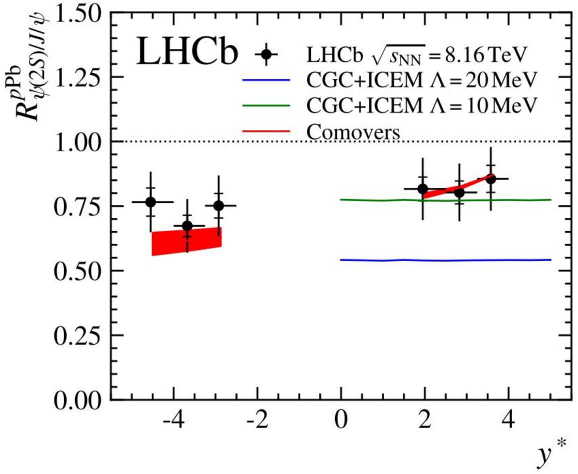
- Non-prompt double ratio consistent with unity, affected by *b* production only
- Prompt double ratio lower than one, $\psi(2S)$ is affected more by final-state effects, given J/ψ is mainly affected by initial-state effects [PLB774, 159 (2017)]
- Only prompt double ratio is suppressed, consistent with co-mover model [PLB749m 98(2015)]

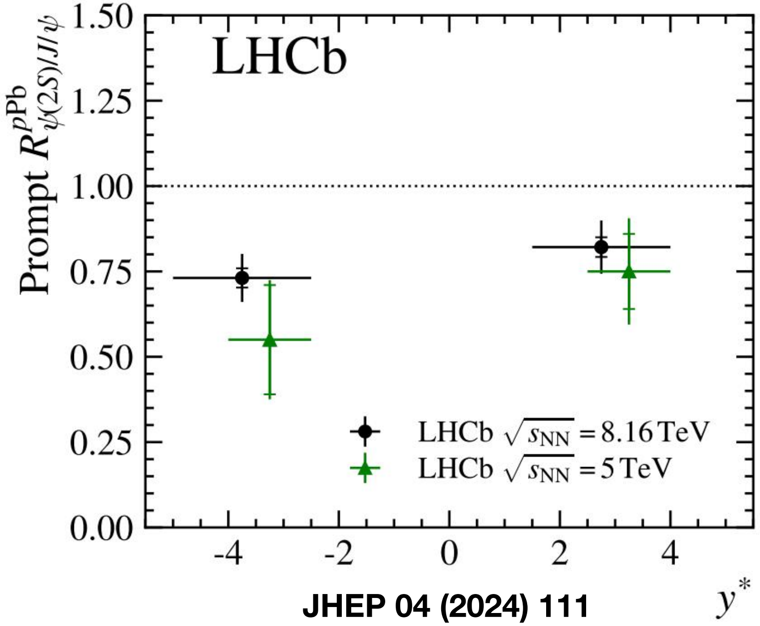
$\psi(2S)$-to-J/ψ double ratio at $\sqrt{s_{NN}} = 8.16$ TeV

$$R^{p\mathrm{Pb}}_{\psi(2S)/J/\psi} = \frac{R_{p\mathrm{Pb}}(\psi(2S))}{R_{p\mathrm{Pb}}(J/\psi)} = \frac{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{p\mathrm{Pb}}}{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{pp}}$$

- Initial-state effects canceled
- The prompt double ratio can be explained by co-mover model and CGC+ICEM for appropriate parameters (also applied to lower energy data from RHIC)
- Result consistent with 5 TeV result, a much high precision is achieved







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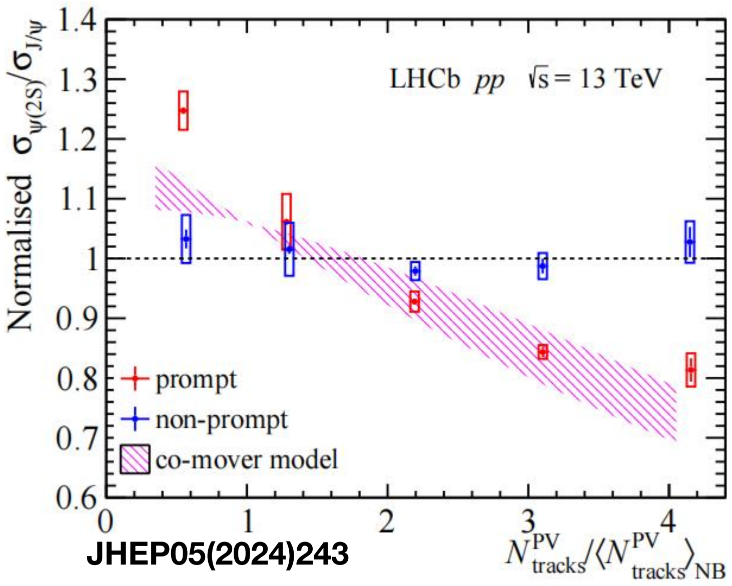
$\psi(2S)$-to-J/ψ production ratio at $\sqrt{s} = 13$ TeV



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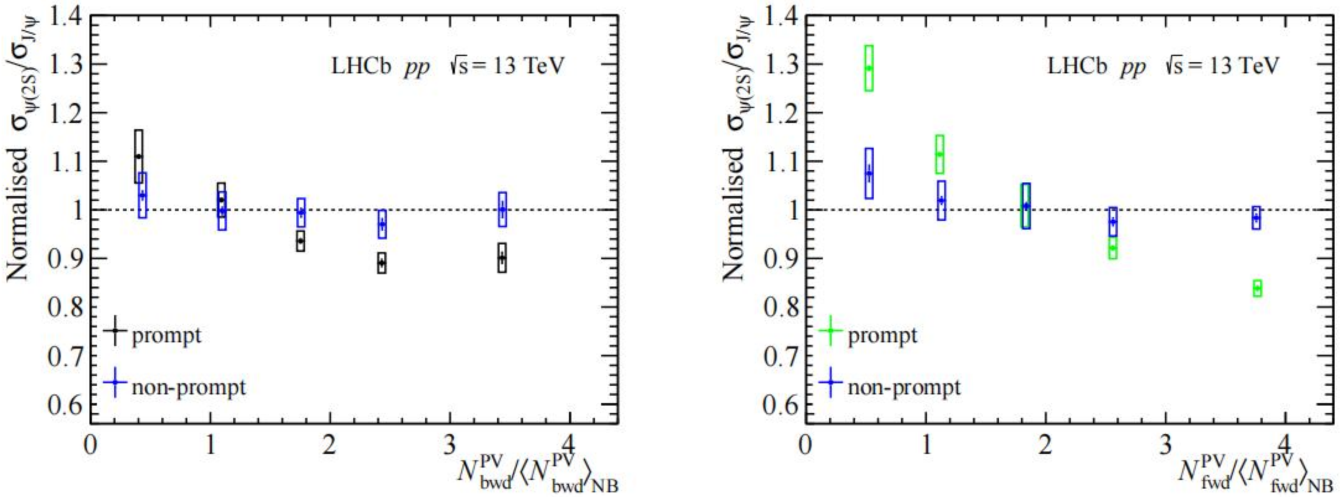
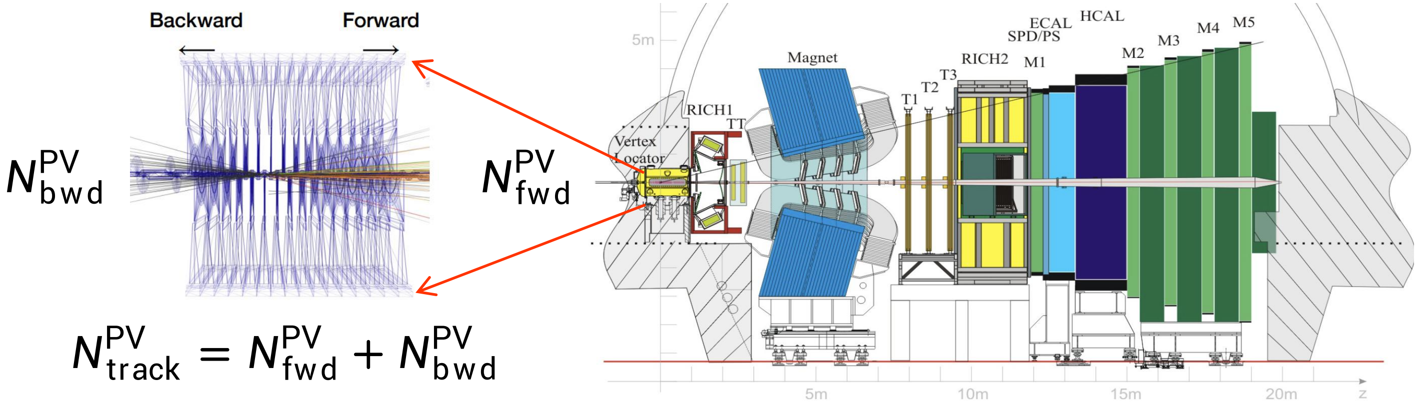
$$\text{Normalised } \sigma_{\psi(2S),n}/\sigma_{J/\psi,n} = \frac{\sigma_{\psi(2S),n}/\sigma_{J/\psi,n}}{\sum_n \sigma_{\psi(2S),n}/\sum_n \sigma_{J/\psi,n}}$$



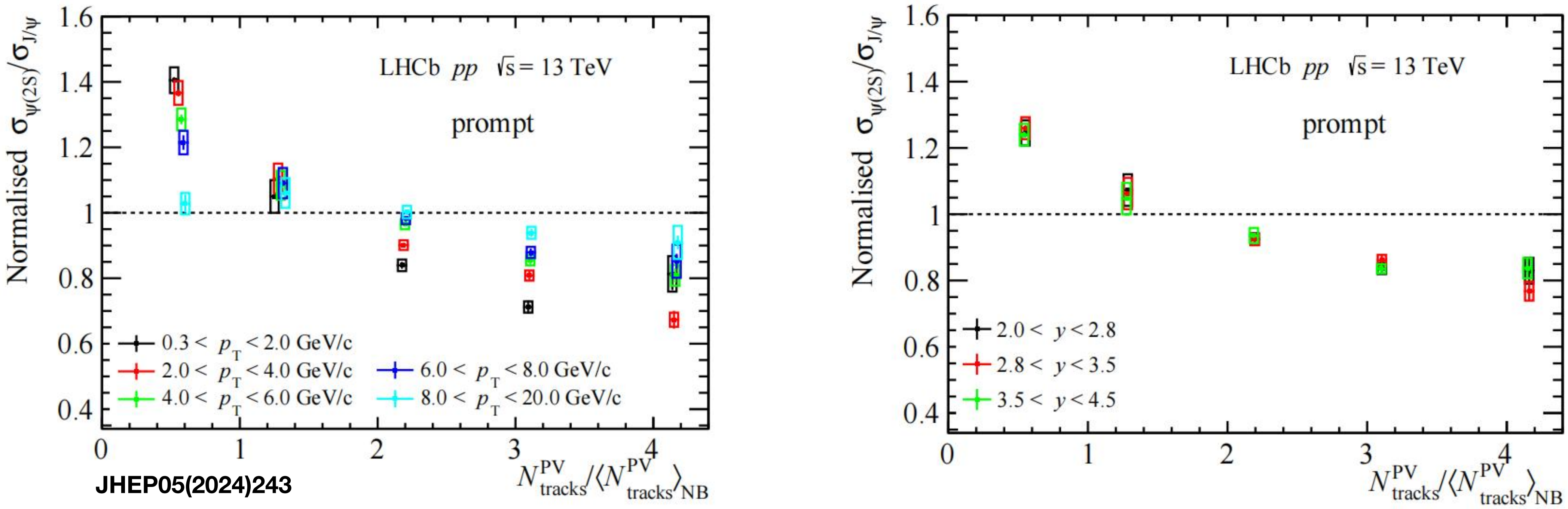
- ➢ Initial-state effects canceled
- ➢ Prompt ratio decrease with multiplicity, highly dependent on forward multiplicity, consistent with co-mover model[PLB749m 98(2015)]
- ➢ Non-prompt ratio independent of any multiplicity variables, consistent with co-mover model



$$N^{PV}_{track} = N^{PV}_{fwd} + N^{PV}_{bwd}$$

JINST 3 (2008) S08005

$\psi(2S)$-to-J/ψ production ratio at $\sqrt{s} = 13$ TeV



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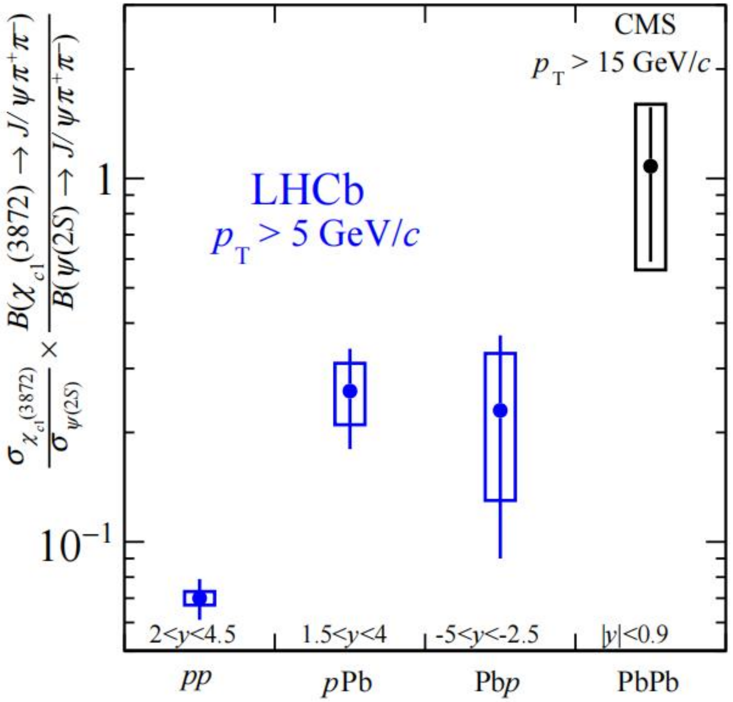
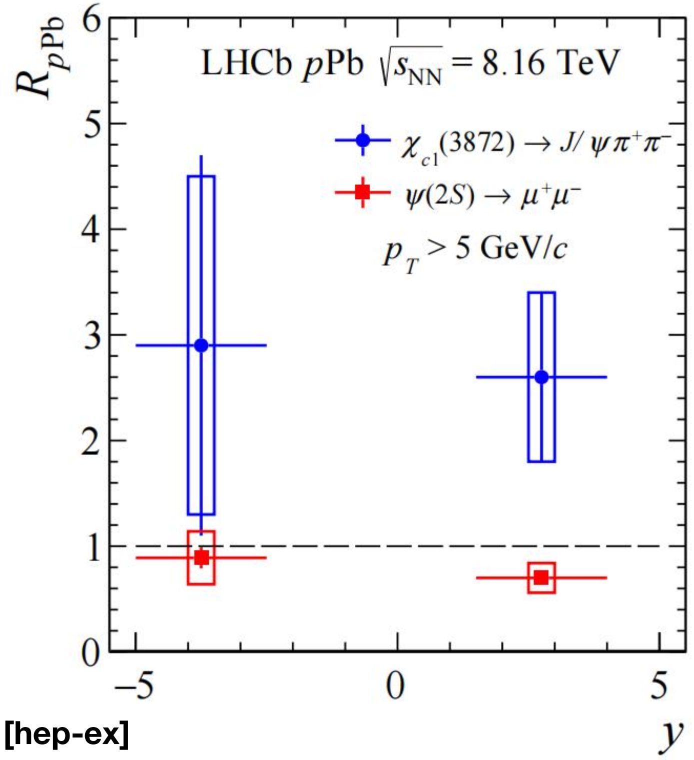
- ➢Prompt ratio show higher dependence on multiplicity at low p_T region
- ➢Prompt ratio show similar dependence on multiplicity in different y regions

$\chi_{c1}(3872)$ relative to $\psi(2S)$

$$R_{pA}^{\chi_{c1}(3872)} = \frac{\sigma_{pA}^{\chi_{c1}(3872)}}{208 \times \sigma_{pp}^{\chi_{c1}(3872)}} = \frac{1}{208} \frac{\sigma_{pA}^{\chi_{c1}(3872)}}{\sigma_{pp}^{\chi_{c1}(3872)}} \frac{\sigma_{pA}^{\psi(2S)}}{\sigma_{pp}^{\psi(2S)}} \frac{\sigma_{pp}^{\psi(2S)}}{\sigma_{pA}^{\psi(2S)}} = R_{pA}^{\psi(2S)} \frac{\sigma_{pA}^{\chi_{c1}(3872)} / \sigma_{pA}^{\psi(2S)}}{\sigma_{pp}^{\chi_{c1}(3872)} / \sigma_{pp}^{\psi(2S)}}$$



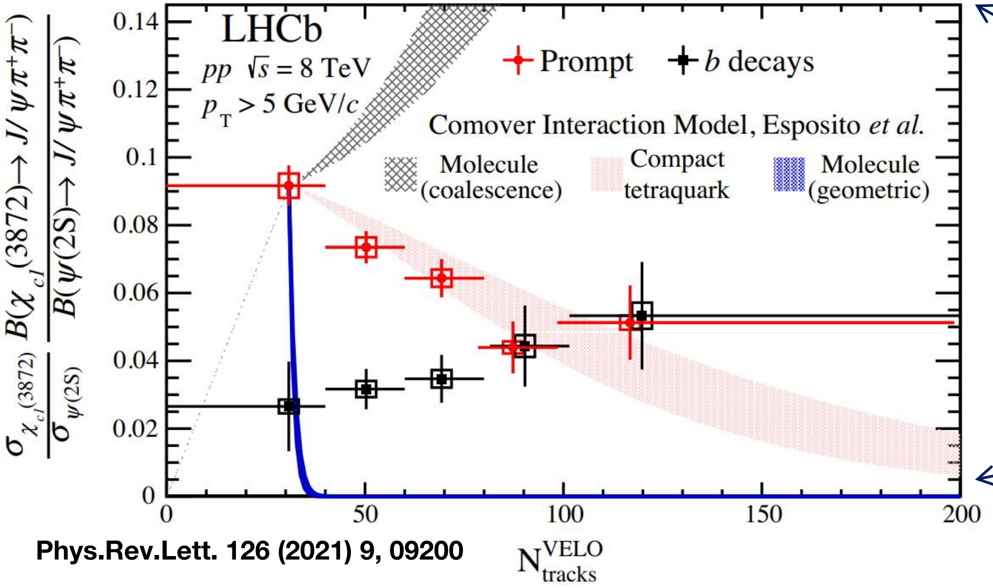
arXiv:2402.14975v1 [hep-ex]



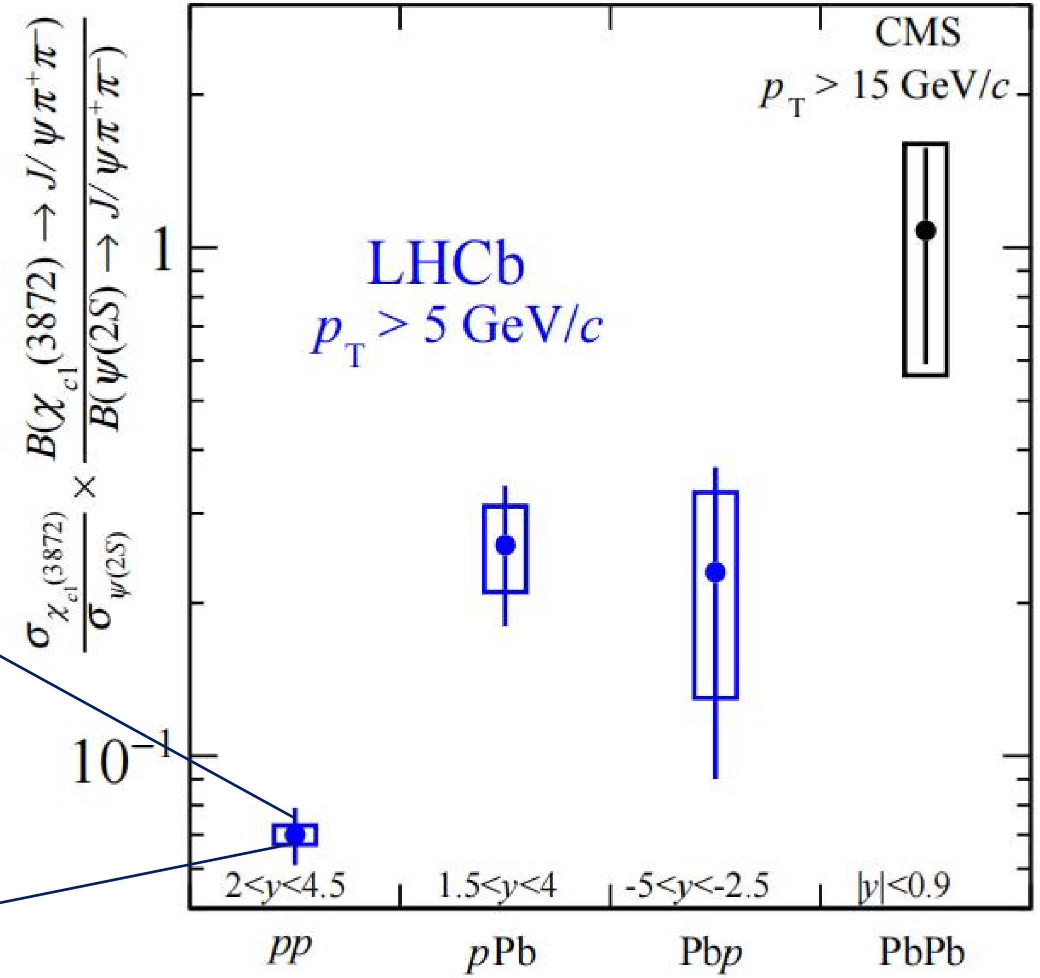
- ➢ The exotic $\chi_{c1}(3872)$ experiences different dynamics than conventional charmonium state $\psi(2S)$

$\chi_{c1}(3872)$ relative to $\psi(2S)$

- Initial-state effects canceled
- Ratio increase with system sizes, but decrease with multiplicity in pp collisions, indicate coalescence is allowed to become the dominant mechanism towards large system
- The exotic $\chi_{c1}(3872)$ experiences different dynamics than conventional charmonium state $\psi(2S)$

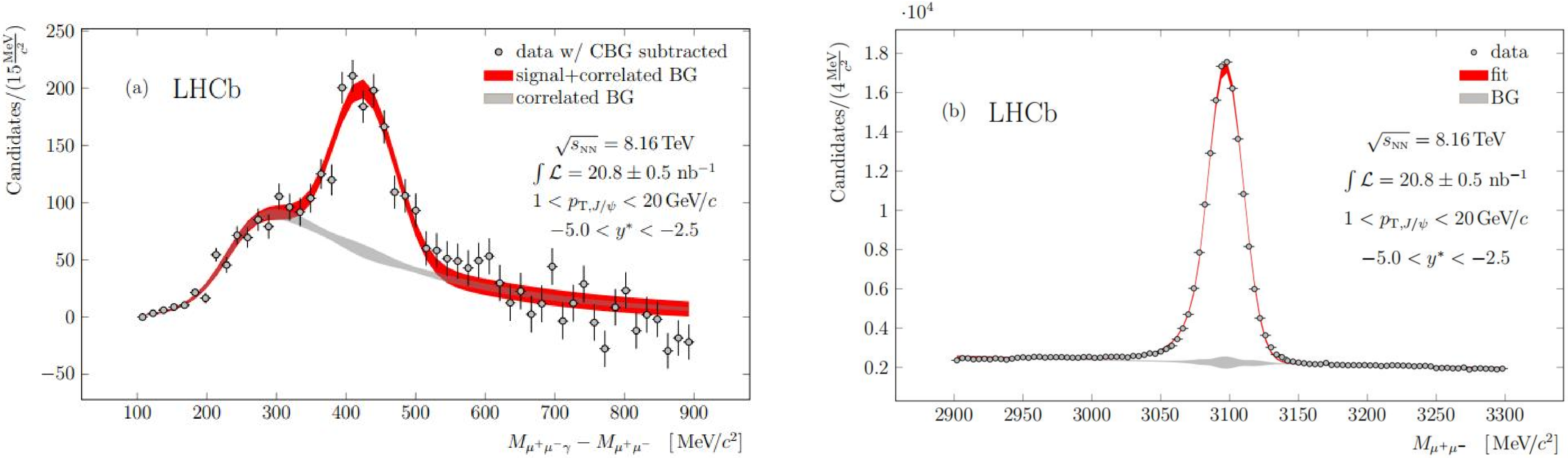


Phys.Rev.Lett. 126 (2021) 9, 09200



arXiv:2402.14975v1 [hep-ex]

χ_c relative to J/ψ



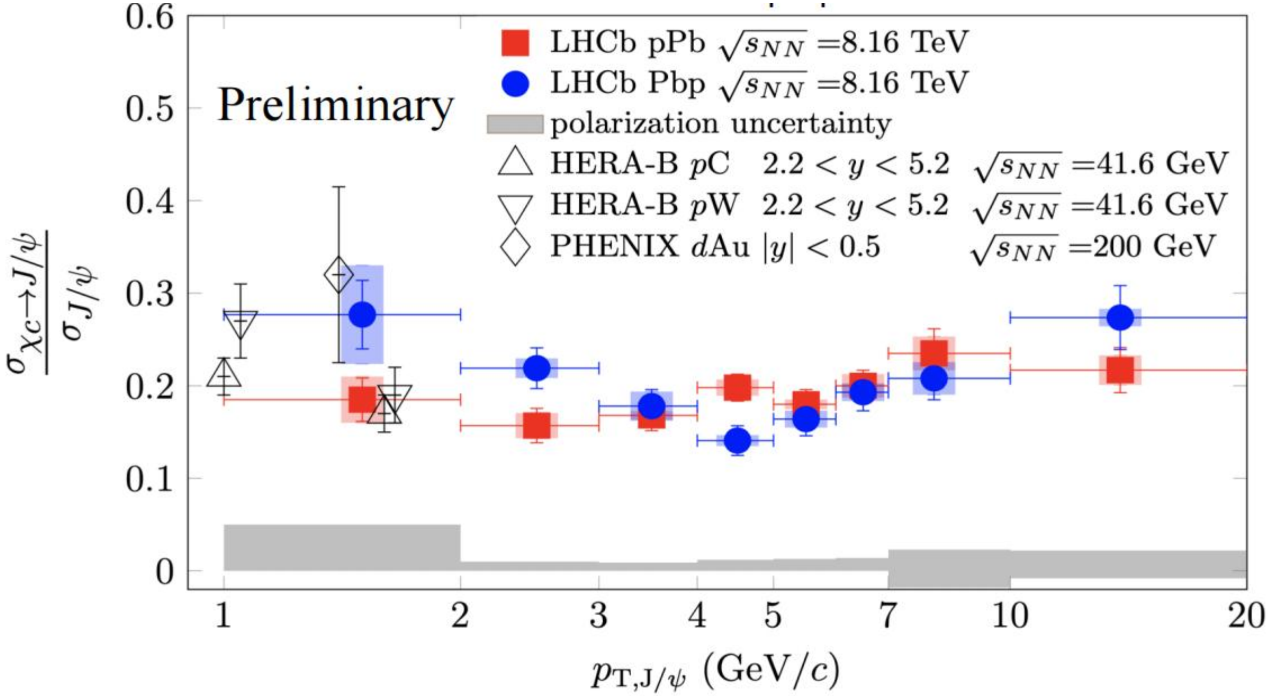
Phys. Rev. Lett. 132 (2024) 102302

- $\chi_{c1} + \chi_{c2}$ measured in $\chi_c \rightarrow J/\psi\gamma \rightarrow \mu^+\mu^-\gamma$
- γ measured by ECAL with $p_T > 0.4$ GeV/c

χ_c relative to J/ψ

- Initial-state effects canceled
- Forward rapidity consistent with *pp* results
- Backward rapidity 2.4 σ higher than the forward for low p_T regions, could result from larger suppression of $\psi(2S)$ in backward
- Result consistent with lower energy measurements from HERA-B and PHENIX.

Phys. Rev. Lett. 132 (2024) 102302



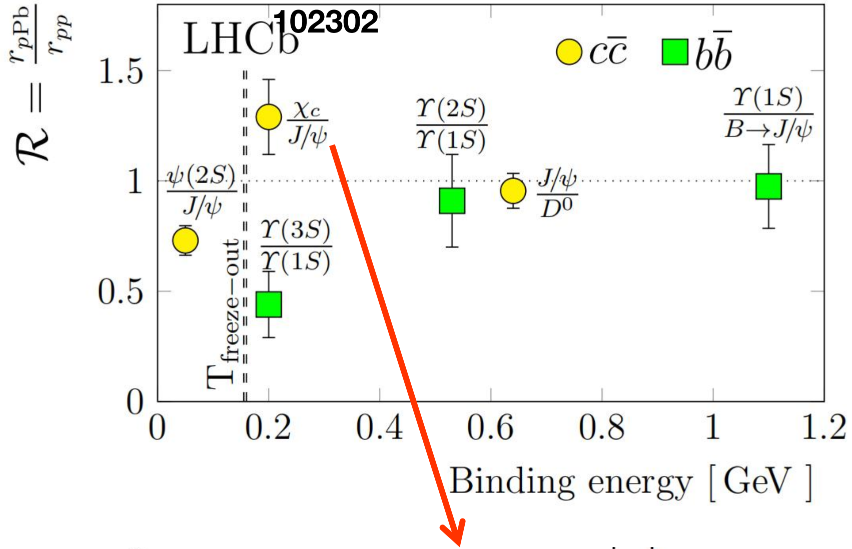
Prompt J/ψ composition:

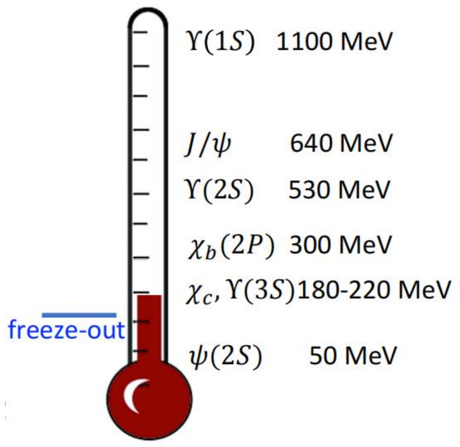
- Direct J/ψ
- $\chi_c \to J/\psi\ \gamma$ decays
- $\psi(2S) \to J/\psi + X$decays
- exotics

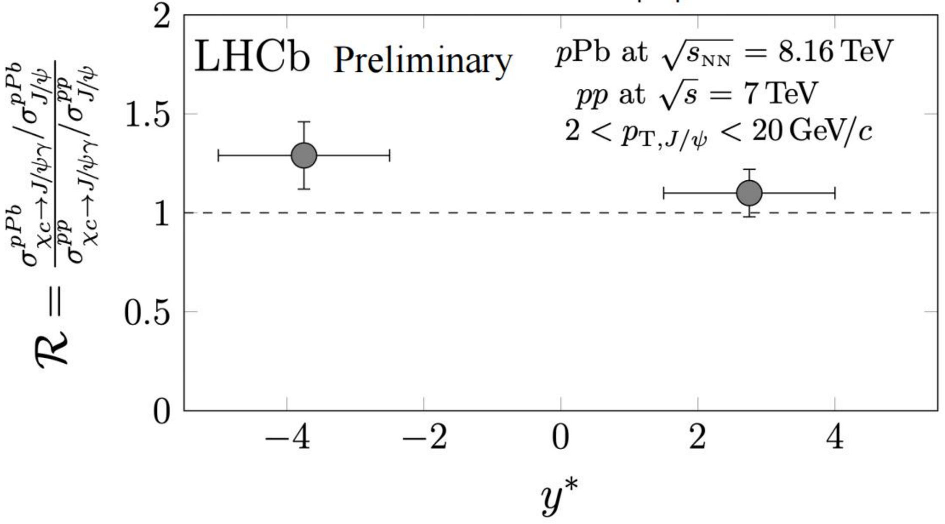
χ_c-to-J/ψ double ratio

- ➢ Initial-state effects canceled
- ➢ No dissociation due to final-state effects for χ_c observed
- ➢ The medium temperature formed in *p*Pb collisions **cannot** inhibit the formation of charmonium states with binding energy larger than 180 MeV
- ➢ $\Upsilon(3S)$ dissociate, with similar size and binding energy, can due to its heavier and slower, more easily interact with co-mover

Phys. Rev. Lett. 132 (2024) 102302



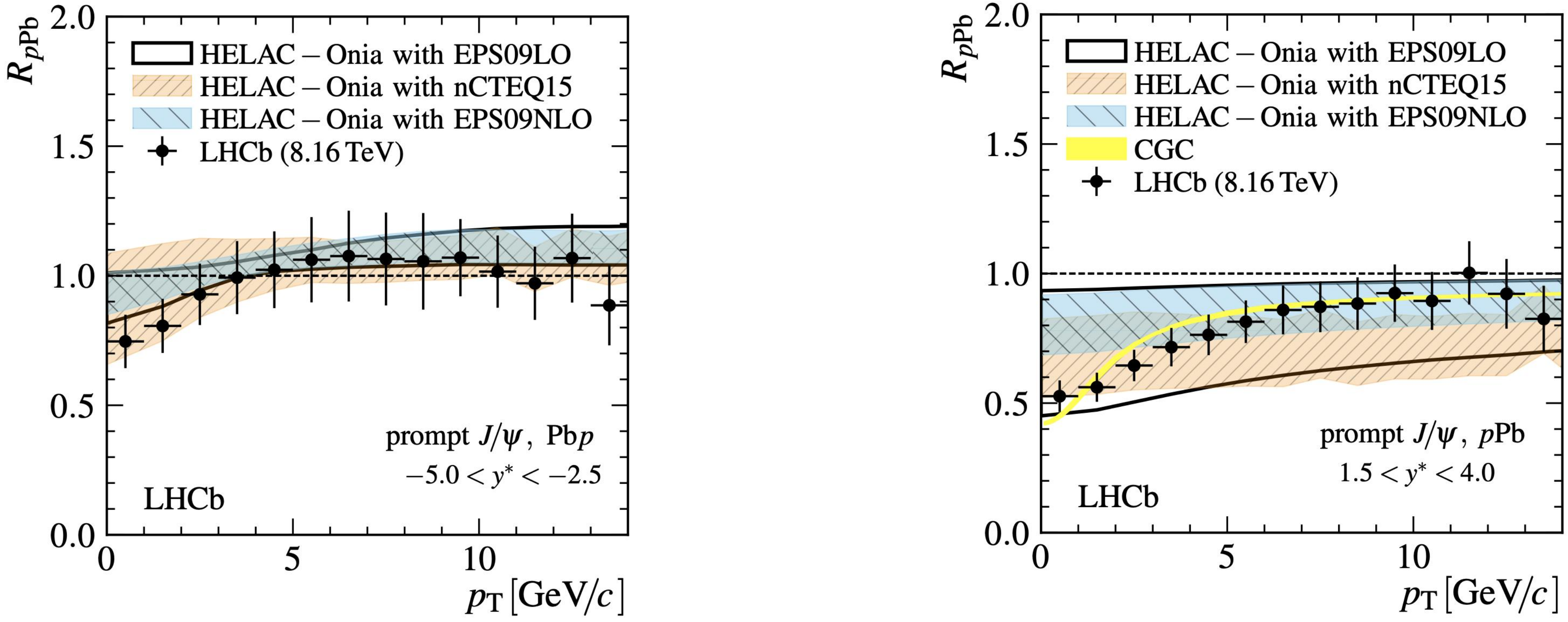




Summary

- Result of $\psi(2S)$, J/ψ, and χ_c in *pp* and *p*Pb collisions are presented
- The $\psi(2S)$ is influenced by final-state effects in *pp* and *p*Pb collisions
- The exotic $\chi_{c1}(3872)$ is found to experience different dynamics than conventional charmonium
- The χ_c is not inhibit to produce in *p*Pb collisions with its binding energy only 20MeV above freeze-out temperature

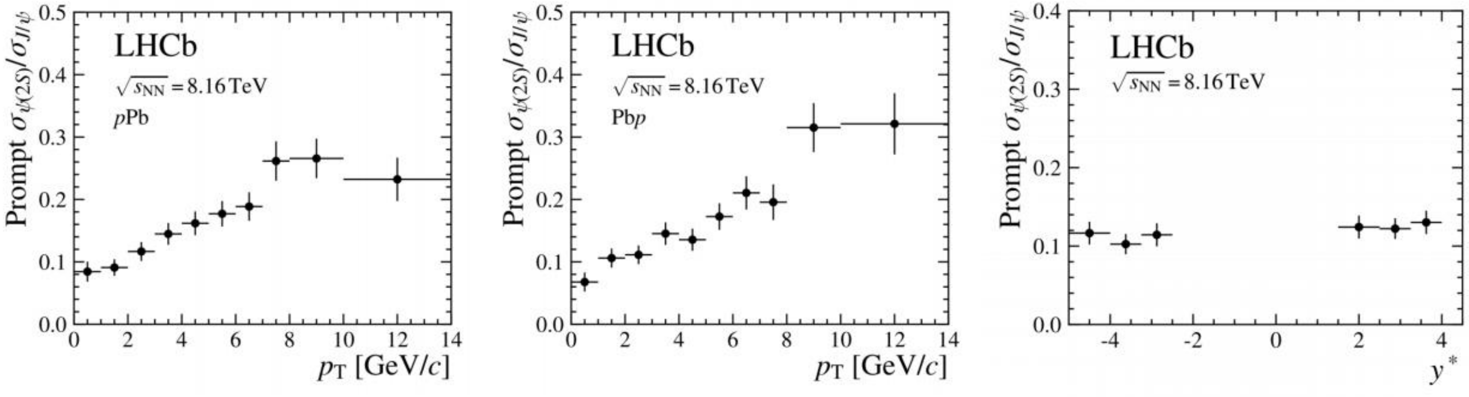
BackUp 1: Jpsi, Initial state effect



PLB774, 159 (2017)

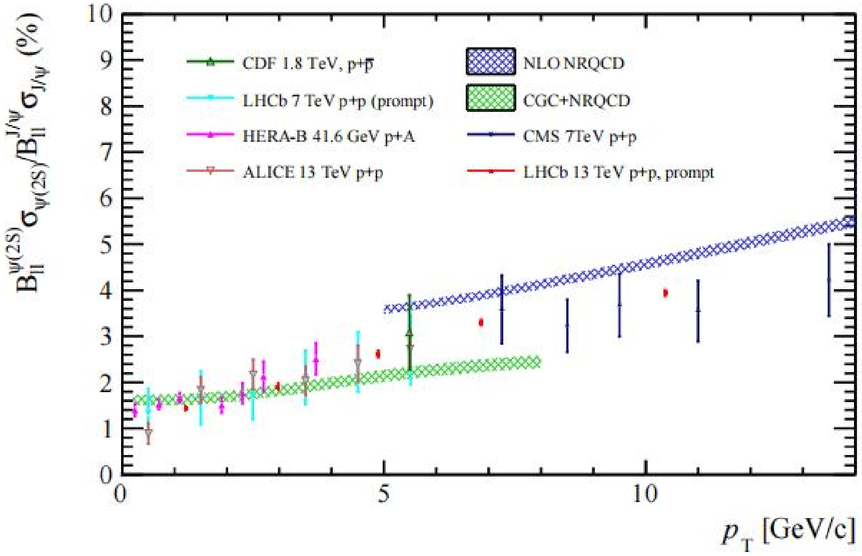
J/ψ nuclear modification factor largely comes from Initial-State Effects

BackUp 2: pT spectrum of psi2s/Jpsi



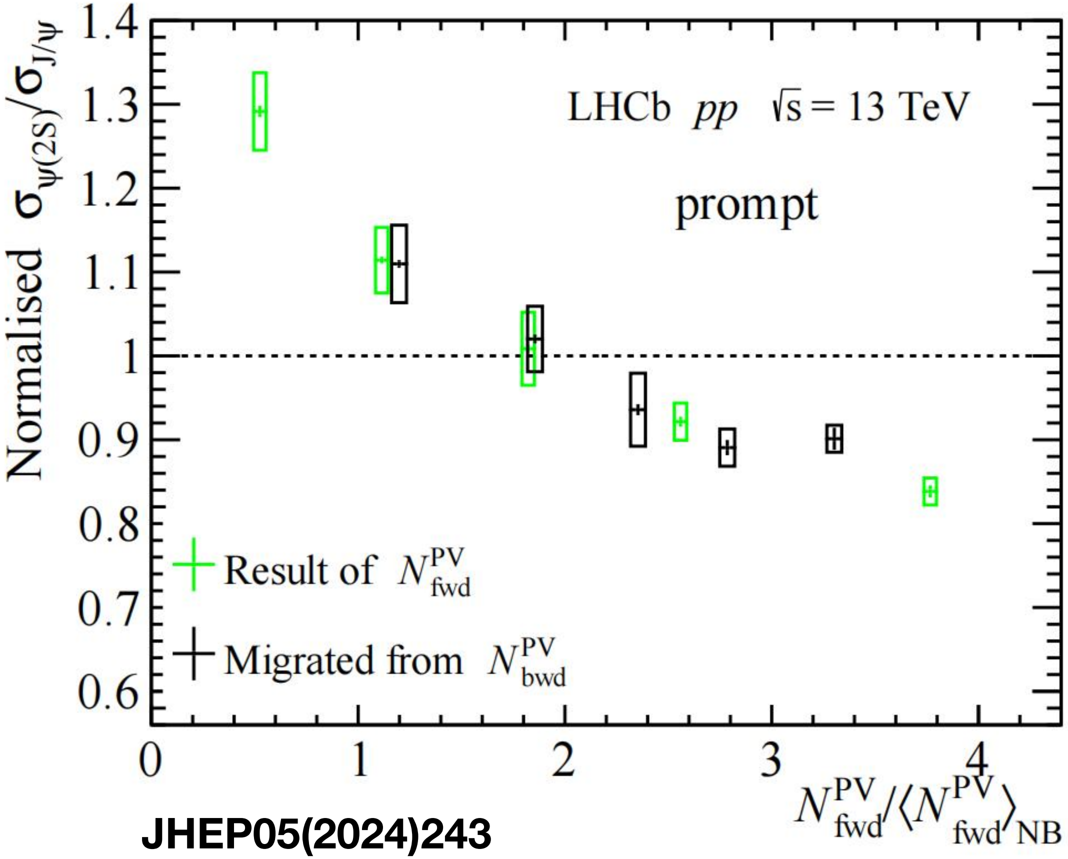
$$\frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}}$$

- increases with p_T
- flat in rapidity



pp 13TeV results

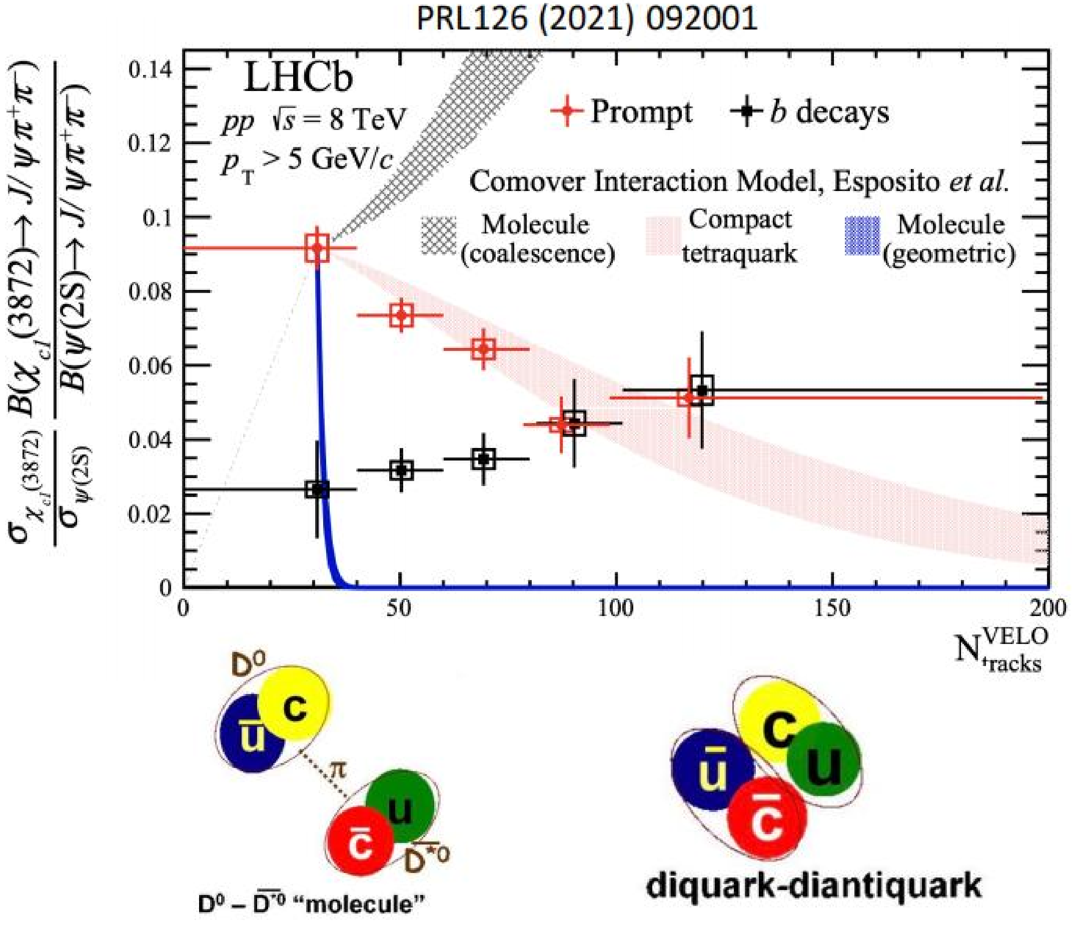
BackUp 3: Back- and For-ward mul.



JHEP05(2024)243

Dependence on backward multiplicity might come from the correlation between forward and backward multiplicity.

BackUp 4: X(3872) molecule, tetra-quark?



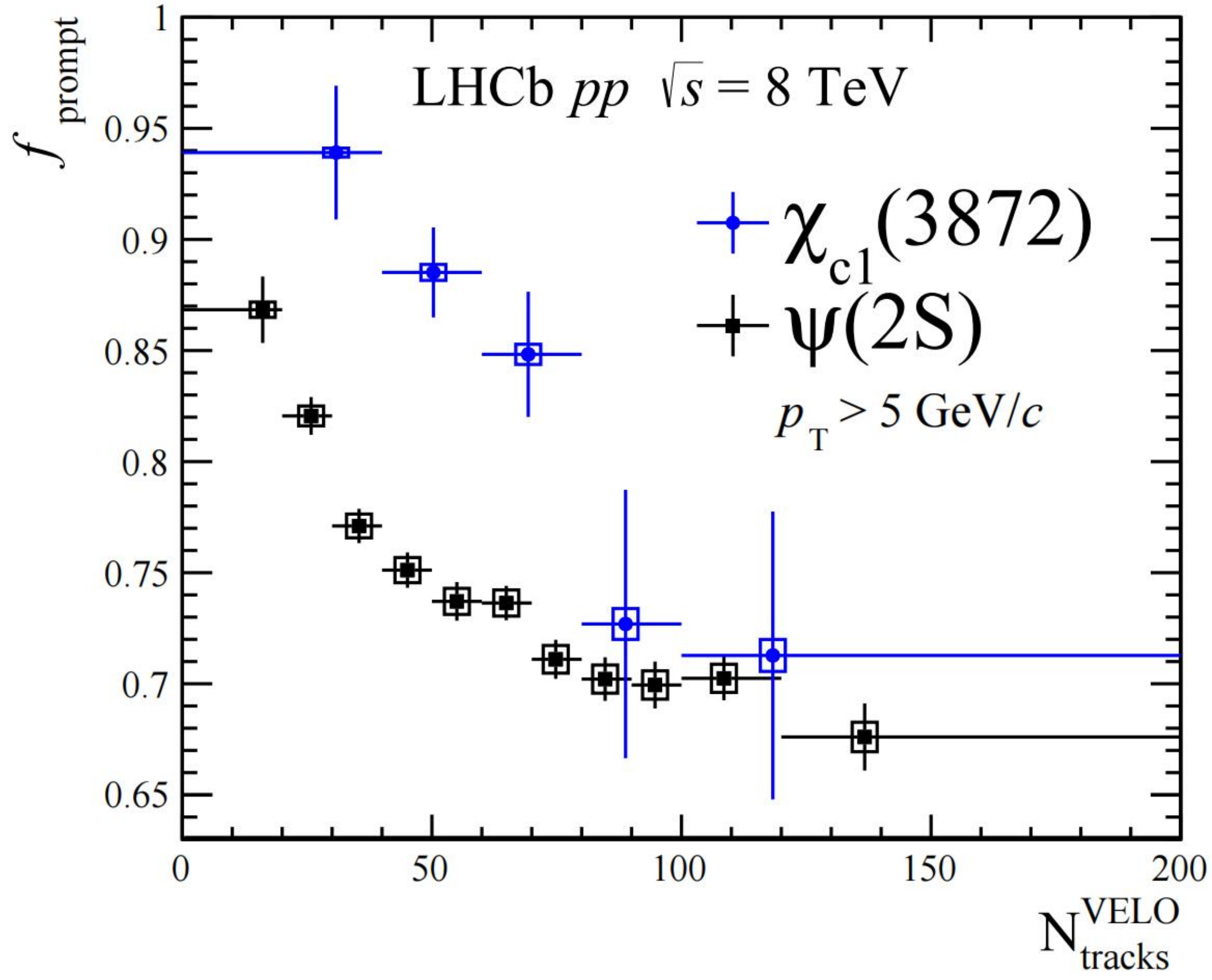
PRL126 (2021) 092001

Suppression of $\chi_{c1}(3872)$ relative to $\psi(2S)$ at high multiplicity pp events.

Consistent with dissociation of a compact tetraquark in comoving particles.

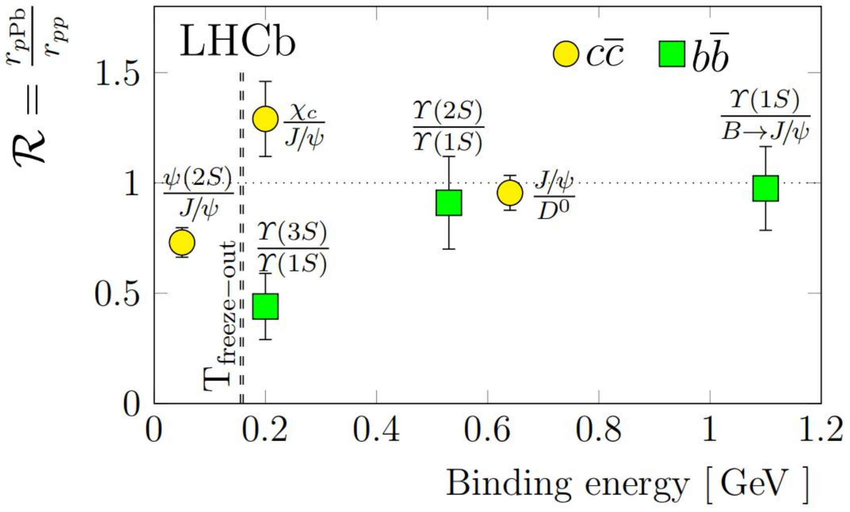
Molecular explanation from Bratten

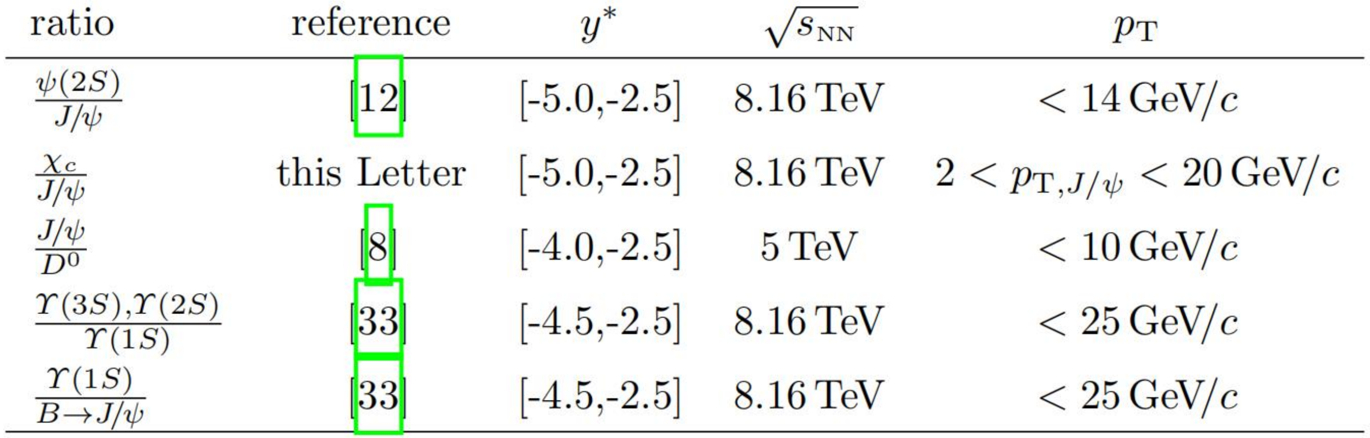
BackUp 5: prompt proportion X(3872), psi(2S)



Prompt proportion decrease with multiplicity, but still be the main component in different multiplicity regions.

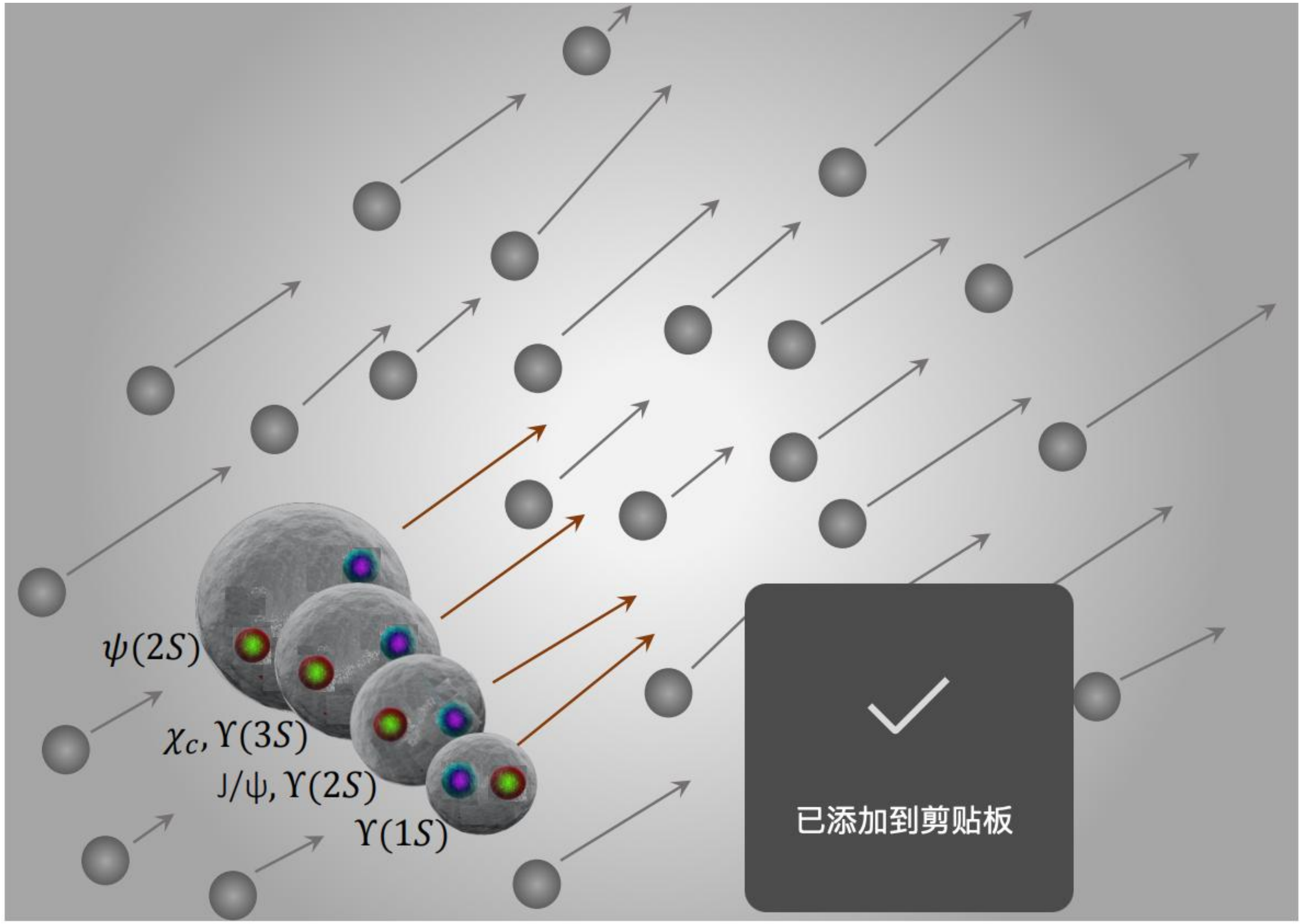
BackUp 6: Chi_c1 to J/psi





ratio	reference	y^*	$\sqrt{s_{\mathrm{NN}}}$	p_{T}
$\frac{\psi(2S)}{J/\psi}$	[12]	[-5.0,-2.5]	8.16 TeV	$< 14\,\mathrm{GeV}/c$
$\frac{\chi_c}{J/\psi}$	this Letter	[-5.0,-2.5]	8.16 TeV	$2 < p_{\mathrm{T},J/\psi} < 20\,\mathrm{GeV}/c$
$\frac{J/\psi}{D^0}$	[8]	[-4.0,-2.5]	5 TeV	$< 10\,\mathrm{GeV}/c$
$\frac{\Upsilon(3S),\Upsilon(2S)}{\Upsilon(1S)}$	[33]	[-4.5,-2.5]	8.16 TeV	$< 25\,\mathrm{GeV}/c$
$\frac{\Upsilon(1S)}{B\to J/\psi}$	[33]	[-4.5,-2.5]	8.16 TeV	$< 25\,\mathrm{GeV}/c$

BackUp 7: radii



	$r(fm)$
J/ψ	0.50
χ_c	0.72
$\psi(2S)$	0.90
$\Upsilon(1S)$	0.28
χ_b	0.44
$\Upsilon(2S)$	0.56
$\chi_b(2P)$	0.68
$\Upsilon(3S)$	0.78

Non-Relativistic Potential Theory:
Satz, J.Phys.G32:R25 (2006)