Quakonium and related observables from proton-proton to heavy-ion collisions

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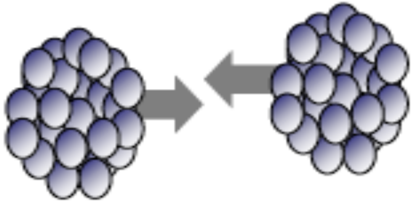
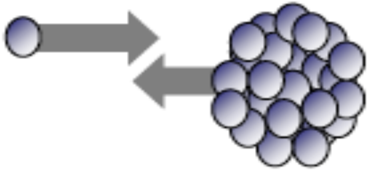
Old paradigm: the three systems (understanding before 2012)

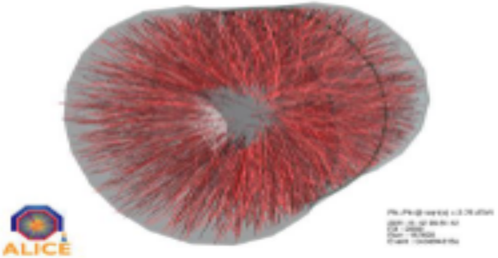
Pb-Pb

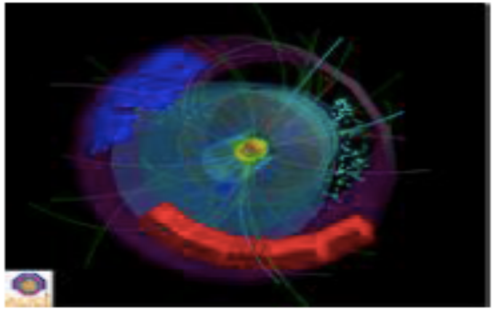


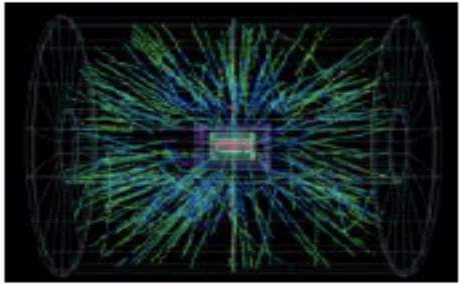
pp

p-Pb









Hot QCD matter:
This is where we expect the QGP to be created in central collisions

QCD baseline:
This is the baseline for “standard” QCD phenomena

Cold QCD matter:
This is to isolate nuclear effects in absence of QGP, e.g. nuclear pdfs

New paradigm: small systems

Totally unexpected:

the discovery of correlations –ridge, flow- in small systems pA & pp

- Smooth continuation of heavy ion phenomena to small systems and low density
- Small systems as pA and pp show QGP-like features

Two serious contenders remain today:

- initial state: quantum correlations as calculated by CGC
- final state: with (hydrodynamics) or without equilibration

The old paradigm that

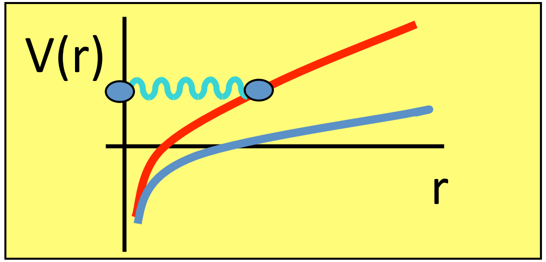
- we study hot & dense matter properties in heavy ion AA collisions
- cold nuclear matter modifications in pA
- and we use pp primarily as comparison data appears no longer sensible

We should examine a new paradigm, where the physics underlying collective signals can be the same in all high energy reactions, from pp to central AA

Why quarkonia? A little bit of history

Potential between q-anti-q pair grows linearly at large distances

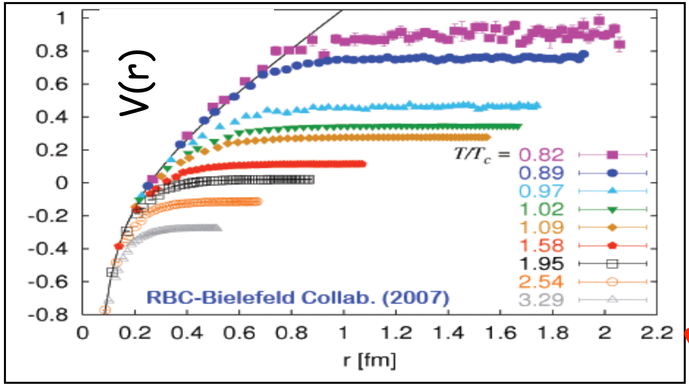
$$\mathrm{V(r)} = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$



Screening of long range confining potential at high enough temperature or density.

$$V(r) = -\frac{\alpha}{r} + kr \longrightarrow V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

Debye screening radius λ_D(T) depends on temperature



What happens when the range of the binding force becomes smaller than the radius of the state? **r > λ_D**

different states "melting" at different temperatures due to different binding energies: **Debye screening**

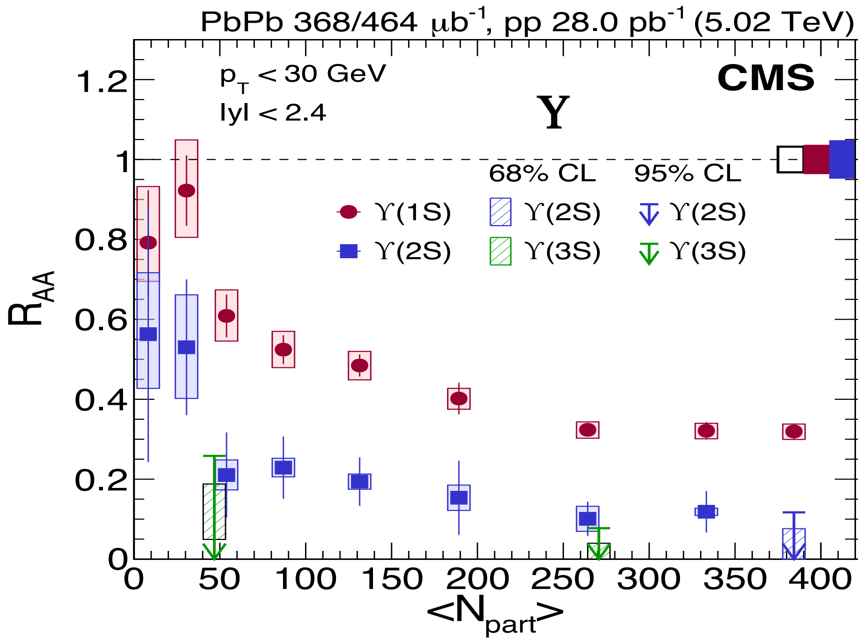
Quarkonia as a QGP thermometer

Measuring nuclear effects: the nuclear modification factor AA

Nuclear modification factor R_{AA}

$$R_{AA} = \frac{d^2N^{pA}/dp_T d\eta}{N_{coll}\, d^2N^{pp}/dp_T d\eta}$$

- R_{AA}<1: suppression
- R_{AA}=1: no nuclear effects
- R_{AA}>1: enhancement



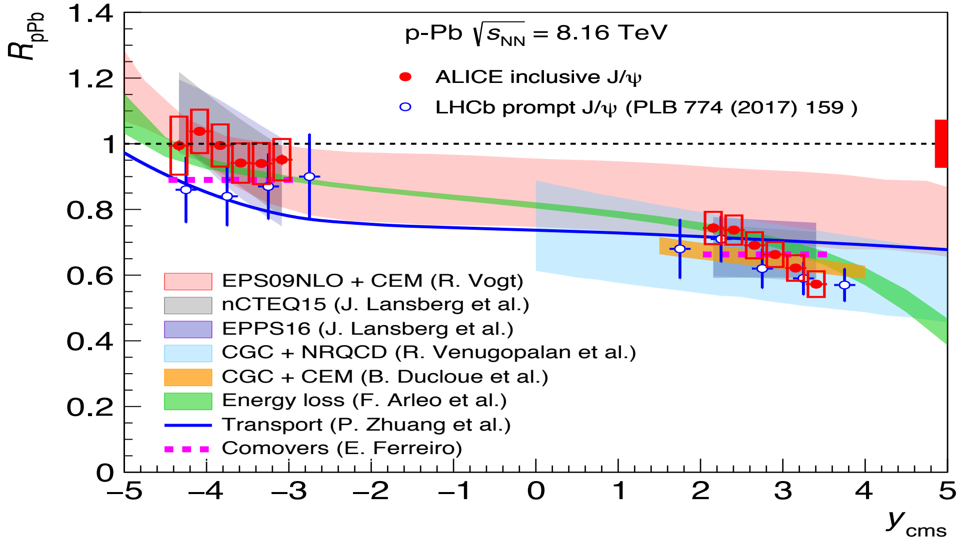
Original motivation to measure quarkonium in nuclear collisions (AA): Signal of QGP
Observable: RAA vs energy density

- The 3 upsilon states are suppressed with increasing centrality

R_{AA}[Y(1S)] > R_{AA}[Y(2S)] > RAA[Y(3S)]

=> Sequential melting

...but the situation is by far much more complicate pA

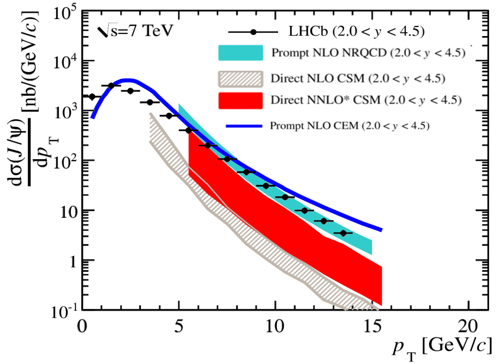


- There are other effects, not related to colour screening, that induce suppression of quarkonium states
- These effects are not all mutually exclusive
- They should be also taken into account in AA collisions

- Modification of the gluon flux *initial-state effect*
  - Nuclear PDF in nuclei: nPDF shadowing
  - Gluon saturation at low x: CGC
- Parton propagation in medium *initial/final effect*
  - Coherent energy loss
- Quarkonium-hadron interaction *final-state effect*
  - Comover interaction
  - Nuclear break-up
- QGP-like effects?

...but the situation is by far much more complicate pp

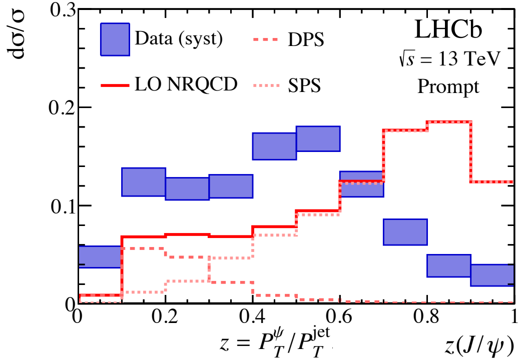
- **Fragmentation of J/ψ in jets:** J/ψ much less isolated in data than predicted by LO NRQCD

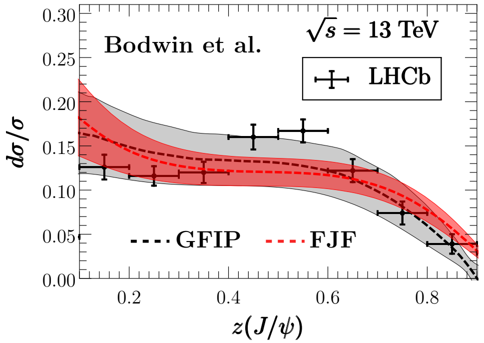


CS: no gluon radiation

CO: soft gluon radiation only

J/ψ produced isolated



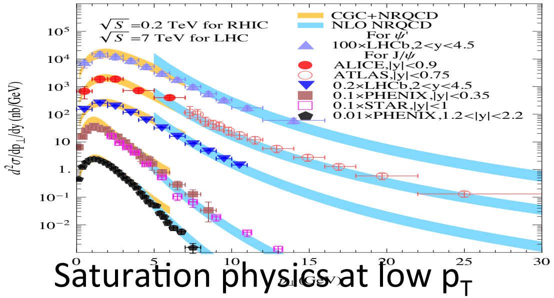


NLL': a hard gluon is first produced

J/ψ produced at later times

Our interpretation of R_{AA} relies on the assumption of cc produced *before* the QGP

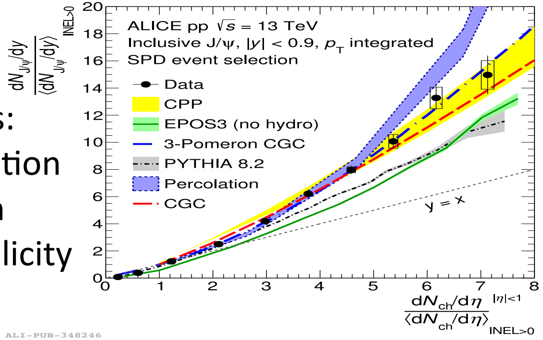
- **Quarkonium vs multiplicities** can improve our understanding of the initial & final effects

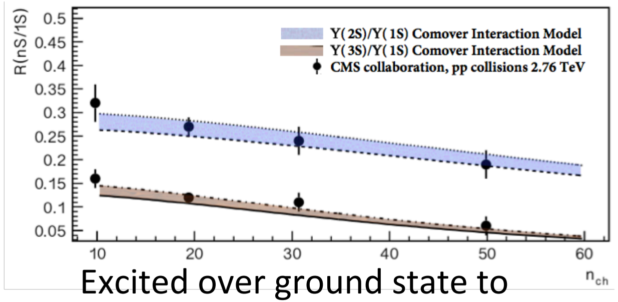


Saturation physics at low p_T

collinear factorization at high p_T

Initial-state effects: Saturation in high multiplicity pp?



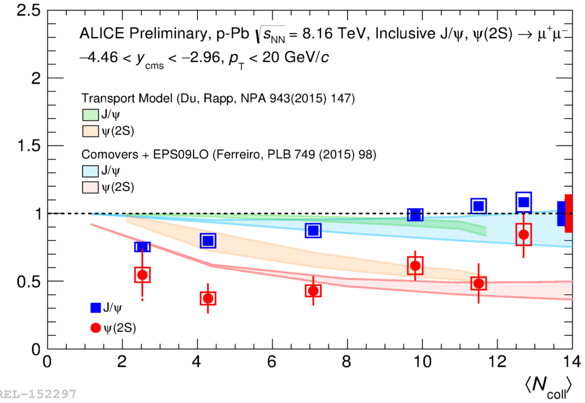


Excited over ground state to measure final-state effects

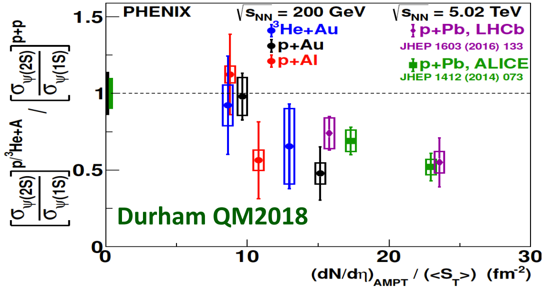
Excited states: Comover interaction

Transport model with final interactions **Du & Rapp (2015)**

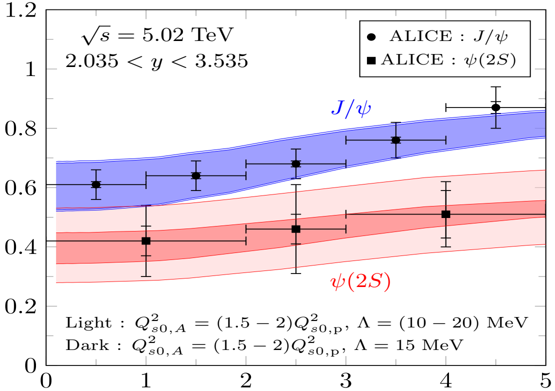
"similar in spirit to comover suppression"

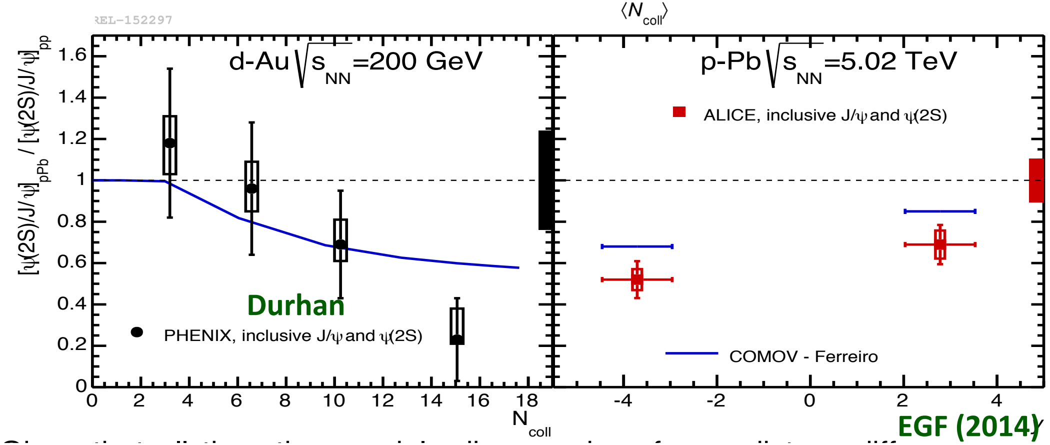


Direct comparison with LHC data as function of comoving particle density



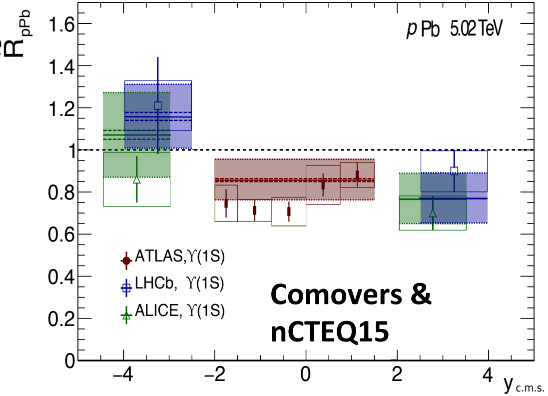
Soft color exchanges between $c\bar{c}$ & comovers at later stage **Ma, Venugopalan, Zhang, Watanabe (2018)**





EGF (2014)

Initial state effects -CGC, nPDFs- cancel in the double ratio



EGF & Lansberg (2018)

Comover-interaction model CIM

- In a comover model: suppression from scatterings of the nascent $\mathcal{Q}$ with comoving medium constituted by particles with similar rapidities **Gavin, Vogt, Capella, Armesto, Ferreiro … (1997)**

- Stronger suppression where the comover densities (multiplicities) are large
  For asymmetric collisions as p-nucleus, stronger in the nucleus-going direction

- Boltzman equation governing the quarkonium density:

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

$\sigma^{co-\mathcal{Q}}$: cross section of quarkonium dissociation due to interactions with comoving medium

- Survival probability from integration over time:

$$S^{co}_{\mathcal{Q}}(b,s,y) = \exp\left\{-\sigma^{co-\mathcal{Q}}\,\rho^{co}(b,s,y)\,\ln\left[\frac{\rho^{co}(b,s,y)}{\rho_{pp}(y)}\right]\right\}$$

$\tau_f/\tau_0 = \rho^{co}(b,s,y)/\rho_{pp}(y)$

Comover-interaction model CIM: The interaction cross sections

- Relative suppression of excited Υ: cleanest observable to fix the comover suppression
- 6 $\sigma^{co-\mathcal{Q}_{b\bar{b}}}$ involved [the feed-downs are taken into account]
- Going to a microscopic level

E.G.F., J.P. Lansberg JHEP 10 (2018)

$$\sigma^{\text{co}-\mathcal{Q}}(E^{\text{co}}) = \sigma^{\mathcal{Q}}_{\text{geo}} \times \left(1 - \frac{E^{\mathcal{Q}}_{\text{thr}}}{E^{\text{co}}}\right)^n$$

$$\langle\sigma^{\text{co}-\mathcal{Q}}\rangle(T_{\text{eff}}, n) = \frac{\int_0^\infty dE^{\text{co}}\,\mathcal{P}(E^{\text{co}};T_{\text{eff}})\,\sigma^{\text{co}-\mathcal{Q}}(E^{\text{co}})}{\int_0^\infty dE^{\text{co}}\,\mathcal{P}(E^{\text{co}};T_{\text{eff}})}$$

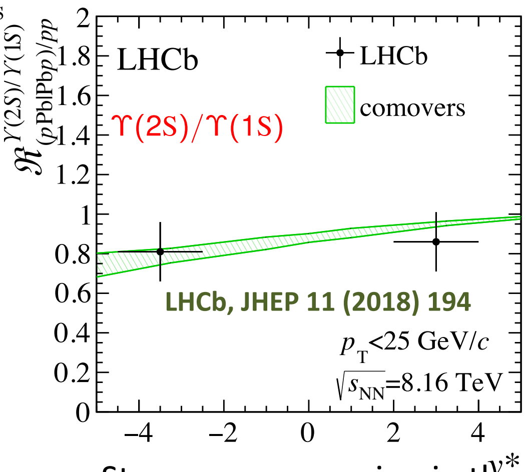
$\sigma^{\mathcal{Q}}_{\text{geo}} \simeq \pi r^2_{\mathcal{Q}}$, where $r_{\mathcal{Q}}$ is the quarkonium Bohr radius

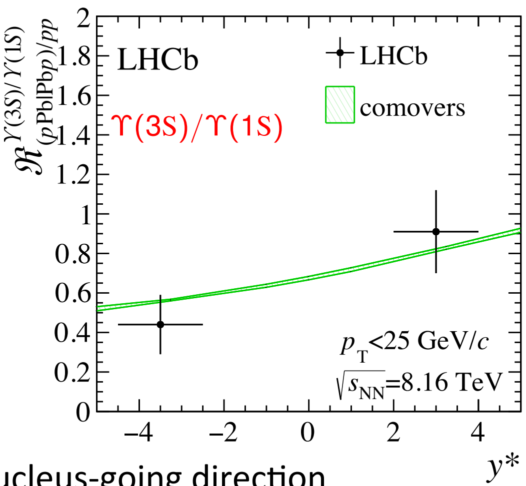
$E^{\mathcal{Q}}_{\text{thr}} = 2M_B - M_{\mathcal{Q}_{b\bar{b}}}$, *i.e.* the threshold energy

$E^{co} = \sqrt{p^2 + m^2_{co}}$ energy of the comovers

Bose-Einstein distribution

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

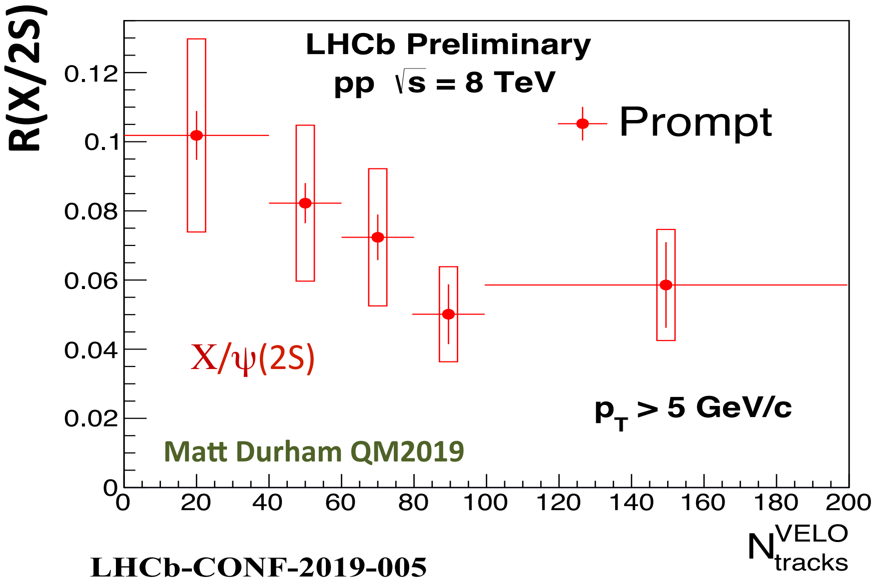




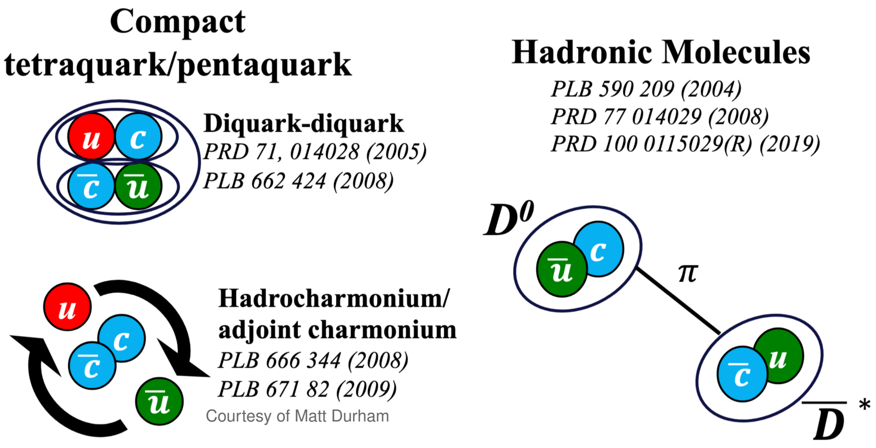
Stronger suppression in the nucleus-going direction

- Succesfully reproduces the excited-over-ground relative suppression versus rapidity

- Motivation: recent LHCb results on X(3872) versus multiplicity

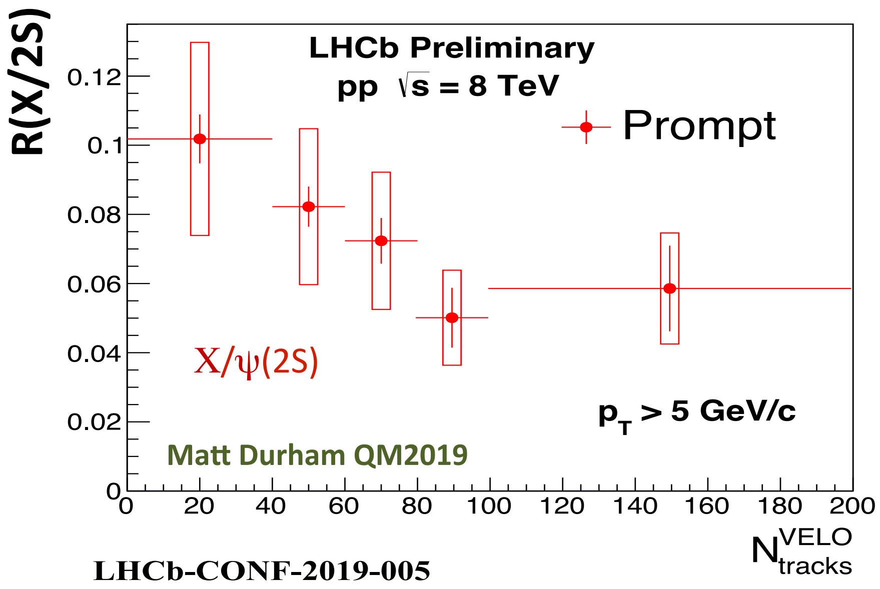


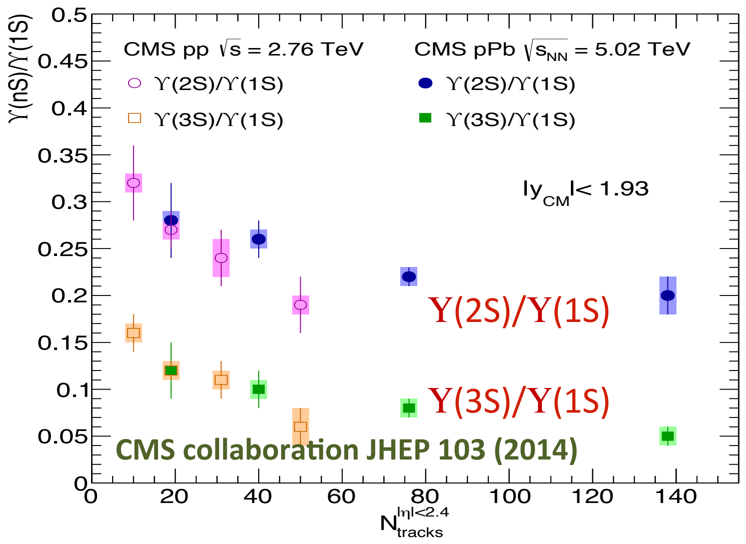
LHCb-CONF-2019-005



Application of final state comover interaction to pp collisions

- In fact, the effect found by LHCb is similar to the one previously found for Υ by CMS





Behaviour of X(3872)/ψ(2S) with multiplicity

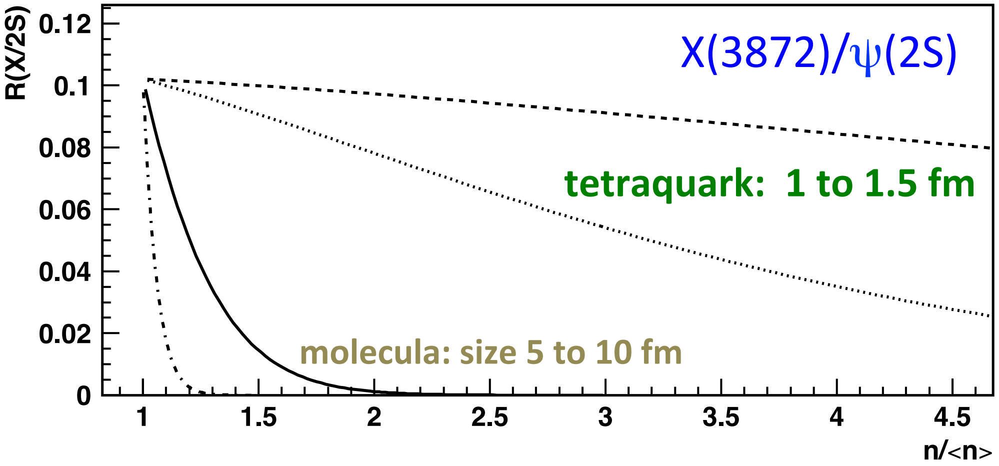
- Let's consider X(3872) as a compact object => interaction cross sections can be calculated

	$E^{\mathcal{Q}}_{\rm thr}$	$r_{\mathcal{Q}}$	$\sigma^{\mathcal{Q}}_{\rm geo}$	$\sigma^{\rm co-\mathcal{Q}}$
$\psi(2S)$	50 MeV	0.45 fm	6.36 mb	5.15 ± 0.84 mb
$X(3872)$ tetraquark	200 keV	0.65 fm	13.3 mb	11.61 ± 1.69 mb
$X(3872)$ molecule	200 keV	5.0 fm	785 mb	687 ± 98 mb

For the 2S: Satz 0512217
For the X tetraquark: Esposito,Polosa 1807.06040
Maiani et al. 0412098
For X molecular: Beveren & Rupp

$$\sigma^{\rm co-\mathcal{Q}}(E^{\rm co}) = \sigma^{\mathcal{Q}}_{\rm geo} \times \left(1 - \frac{E^{\mathcal{Q}}_{\rm thr}}{E^{\rm co}}\right)^n$$

Cross sections very close to their geometrical value due to small binding energies involved



- Cross sections calculated as for Υ
- Parameters involved: size & binding E
- Our results are normalized to the experimental value obtained for the first bin

Behaviour of X(3872)/ψ(2S) with multiplicity

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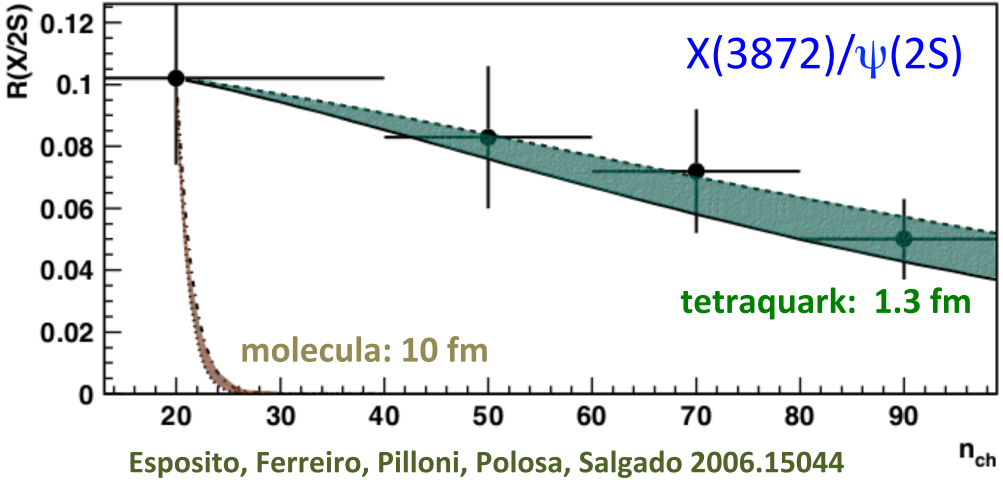

Esposito, Ferreiro, Pilloni, Polosa, Salgado 2006.15044

- LHCb results strongly supports the idea of X(3872) of typical hadronic size
- A molecular state disappears very quickly by interaction with comovers
- Our conclusion: tetraquark of 1.3 fm

Coalescence is not the solution

- Accoding to quarkonium data, no secondary charmonium production has been considered for a X(3872) of typical hadronic size
- In case of a X(3872) of molecular nature, coalescence effects, similar to the ones applied to reproduce d/p ratio in pp, can be at play

$$\boxed{\tau \frac{dN_m}{d\tau} = \langle v\sigma \rangle_m \, \rho_c \, N_{12} - \left(\langle v\sigma \rangle_m + \langle v\sigma \rangle_{hh} \right) \rho_c \, N_m}$$

N_m # of molecules
N_{12} # of constituent pairs (constant in time)

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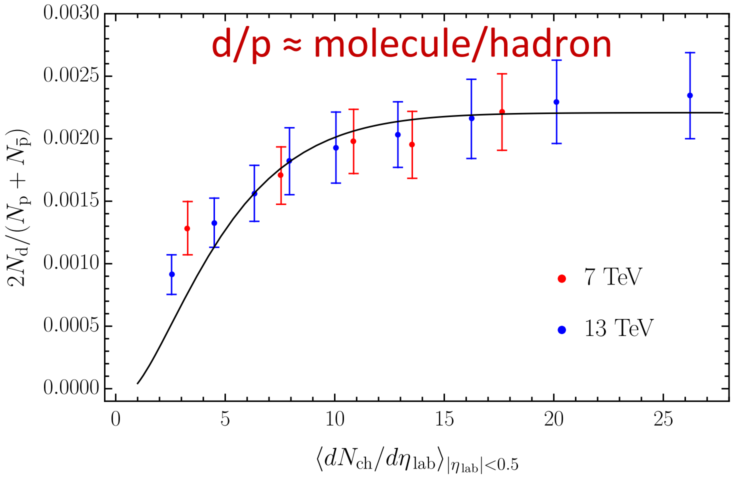

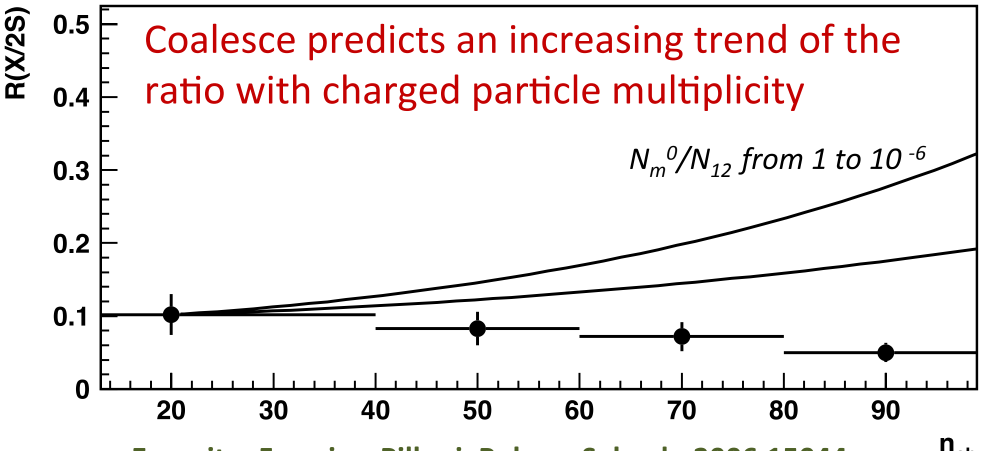

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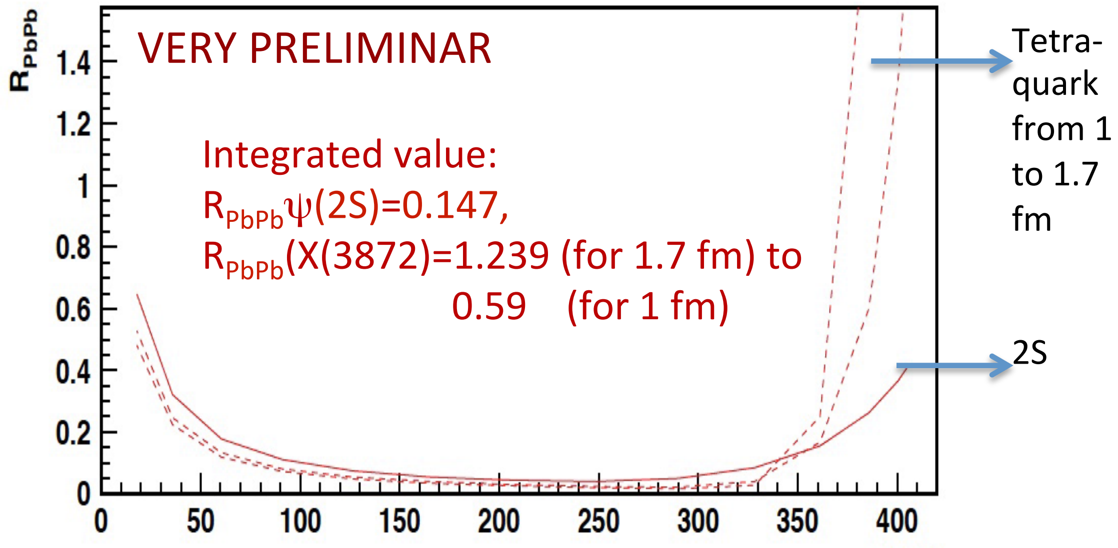
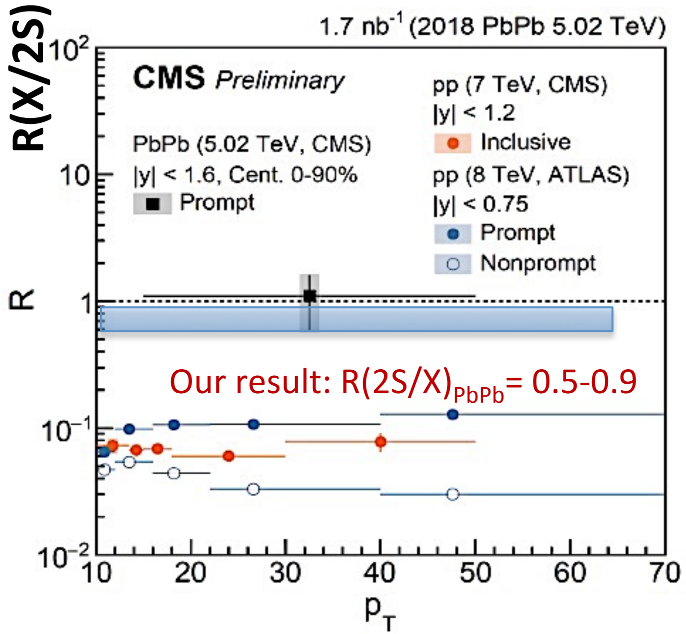
Future X(3872) studies in HI collisions

- For low P_T production, dissociation and recombination of X(3872) similar to those of charmonium can happen in the hot QGP or in the hadronic gas

So far, only the ratio between production yields of X(3872) and Ψ(2S) has been measured by the CMS collaboration in the p_T = 10-50 GeV range





New observables can help

Observables	Experiments	CSM	CEM	NRQCD	Interest
J/ψ+J/ψ	LHCb, CMS, ATLAS, D0 (+NA3)	NLO, NNLO*	LO ?	LO	Prod. Mechanism (CS dominant) + DPS + gluon TMD
J/ψ+D	LHCb	LO	LO ?	LO	Prod. Mechanism (c to J/psi fragmentation) + DPS
J/ψ+ϒ	D0	(N)LO	LO ?	LO	Prod. Mechanism (CO dominant) + DPS
J/ψ+hadron	STAR	LO	--	LO	B feed-down; Singlet vs Octet radiation
J/ψ+Z	ATLAS	NLO	NLO	Partial NLO	Prod. Mechanism + DPS
J/ψ+W	ATLAS	LO	LO ?	Partial NLO	Prod. Mechanism (CO dominant) + DPS
J/ψ vs mult.	ALICE,CMS (+UA1)	--	--	--	Density effects (Saturation/Hydro)
J/ψ+b	-- (LHCb, D0, CMS ?)	--	--	LO	Prod. Mechanism (CO dominant) + DPS
ϒ+D	LHCb	LO	LO ?	LO	DPS
ϒ+γ	--	NLO, NNLO*	LO ?	LO	Prod. Mechanism (CO LDME mix) + gluon TMD/PDF
ϒ vs mult.	CMS	--	--	--	Density effects (Saturation/Hydro)
ϒ+Z	--	NLO	LO ?	LO	Prod. Mechanism + DPS
ϒ+ϒ	CMS	NLO?	LO?	LO?	Prod. Mechanism + DPS + gluon TMD

Lansberg (2018)