Some notes about comovers

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Motivation: the intriguing suppression of excited states in pA

The facts: **data from RHIC & LHC**

- PHENIX: relative $\psi(2S)/J/\psi$ suppression in dAu collisions @ 200 GeV
- ALICE & LHCb: relative $\psi(2S)/J/\psi$ suppression in pPb collisions @ 5 & 8 TeV
- CMS & ATLAS: relative $\psi(2S)/J/\psi$ suppression in pPb collisions @ 5 TeV
- CMS & ATLAS: relative $\Upsilon(nS)/\Upsilon(1S)$ suppression in pPb collisions @ 5 TeV
- LHCb & ALICE: relative $\Upsilon(nS)/\Upsilon(1S)$ suppression in pPb collisions @ 8 TeV

- Initial-state effects –modification of nPDFs / parton E loss- identical for the family
- Any difference among the states should be due to final-state effects

- At low E: relative suppression explained by nuclear absorption $\sigma_{\mathrm{breakup}}\ \alpha\ r^2_{\mathrm{meson}}$
  At high E: too long formation times $t_f = \gamma\, \tau_f >> R$

Consensus: $\sigma_{\mathrm{breakup}}$ is getting small at high energies and may be the same for ground and excited states

A natural explanation would be a final-state effect acting over sufficiently long time $\Rightarrow$ **interaction with a comoving medium?**

Comover-interaction model CIM: Bases

- In a comover model: suppression from scatterings of the nascent $\mathcal{Q}$ with comoving medium of partonic/hadronic origin **Gavin, Vogt, Capella, Armesto, Ferreiro … (1997)**

- By essence of their comoving character, these can interact with the fully formed states after 0.3-0.4 fm/c

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

- Rate equation governing the quarkonium density:

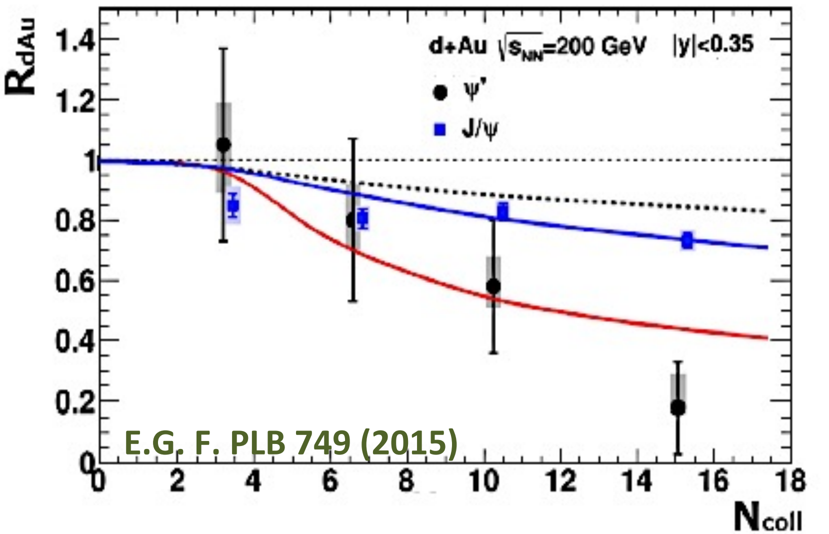
$$\tau \frac{\mathrm{d}\rho^{\mathcal{Q}}}{\mathrm{d}\tau}(b,s,y) = -\sigma^{co-\mathcal{Q}}\,\rho^{co}(b,s,y)\,\rho^{\mathcal{Q}}(b,s,y)$$

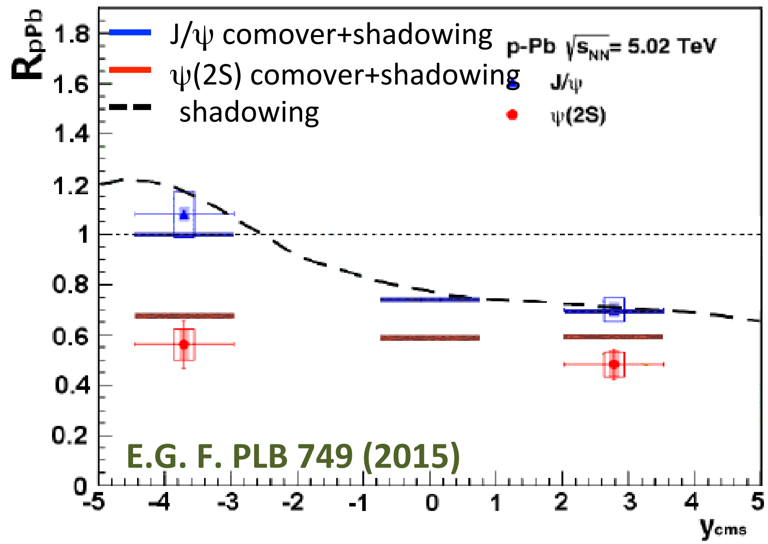
$\sigma^{co-\mathcal{Q}}$ cross section of quarkonium dissociation due to interactions with comoving medium

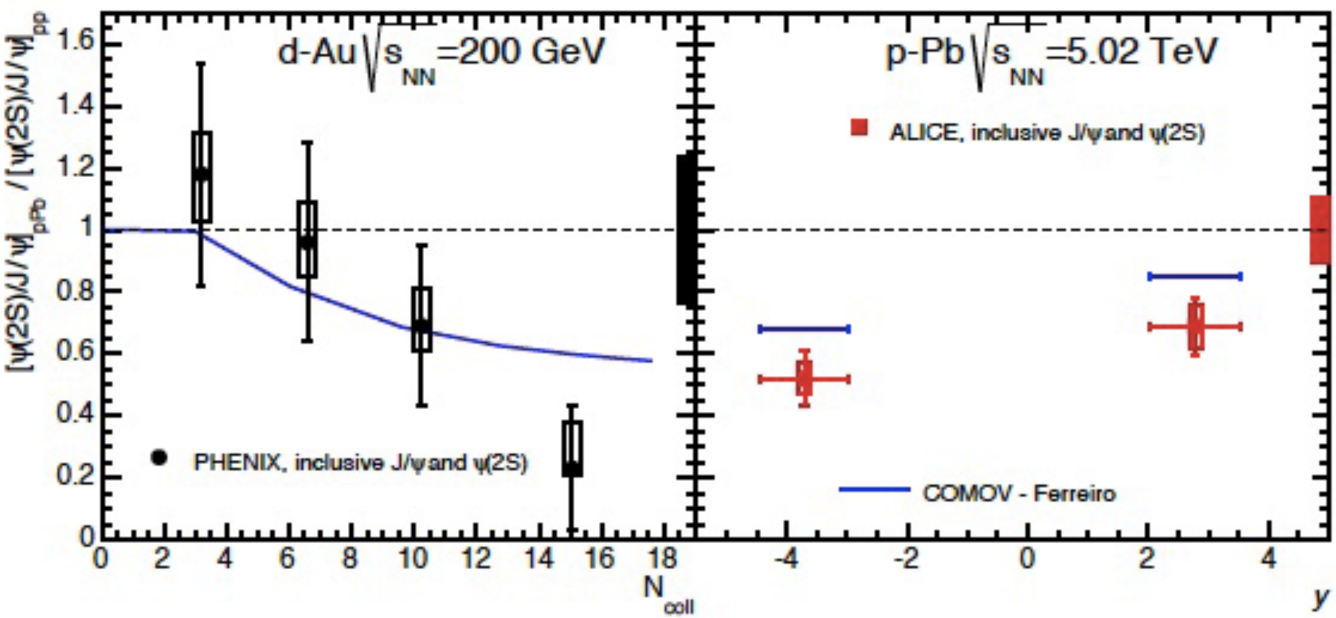
- Survival probability from integration over time: $\tau_f/\tau_0 = \rho^{co}(b,s,y)/\rho_{pp}(y)$

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

$\sigma^{co-\psi}$ originally fitted from SPS data: 0.65 mb for J/ψ and 6 mb for ψ(2)







Pretty encouraging since the data were not fitted

Note that temperature was not mentioned for the moment….

Setting the scene for the bottomonium family

- The bottomonium family is much richer than the charmonium one
- χ_b'' first particle discovered at the LHC **ATLAS PRL 108 (2012) 152001**
- It allows for a much finer studies with 3 Υ states (decaying into dimuons)
- It comprises excited states which are not too fragile [as opposed to e.g. the ψ']

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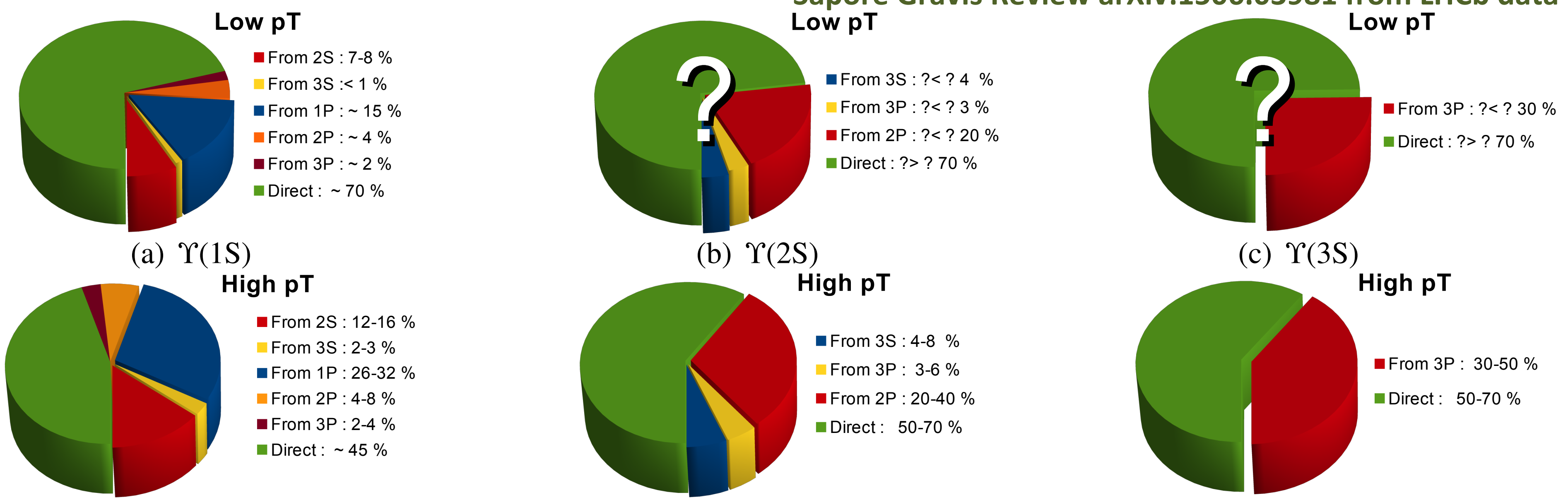
Feed-down structure at low p_T is quite different than CDF measurement at p_T>8GeV

Sapore Gravis Review arXiv:1506.03981 from LHCb data



- **Υ(3S) is far from being 100% direct**
- **In the region of the Υ PbPb and pPb data, the Υ(1S) is not 50% direct**

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- The relative suppression of the excited Υ is probably the cleanest observable to fix the comover suppression magnitude [without interference with other nuclear effect]
- However, not enough data to fit all the 6 $\sigma^{co-\mathcal{Q}_{b\bar{b}}}$ [the feed-downs discussed above were used]
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- We take:

$$\sigma^{co-\mathcal{Q}_{b\bar{b}}} = \sigma_{\mathrm{geom}}\left(1 - \frac{E_{\mathrm{Binding}}}{E_{co}}\right)^{n}$$

E. G. F., J.P. Lansberg, arXiv:1804.04474

$\sigma_{\mathrm{geom}} \equiv \pi r^2_{\mathcal{Q}_{b\bar{b}}}$

$E_{\mathrm{Binding}} \equiv 2M_B - M_{\mathcal{Q}_{b\bar{b}}}$, *i.e.* the threshold energy to break the bound state

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- We average over BE distribution of the comovers $\mathcal{P}(E^{co};T_{\text{eff}}) \propto 1/(e^{E^{co}/T_{eff}} - 1)$

- We derive the energy-averaged quarkonium-comover interaction cross section:

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

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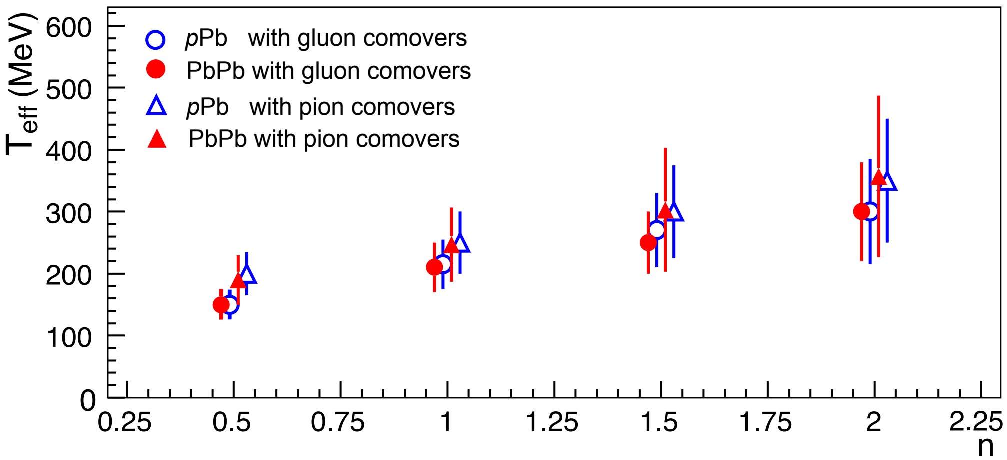
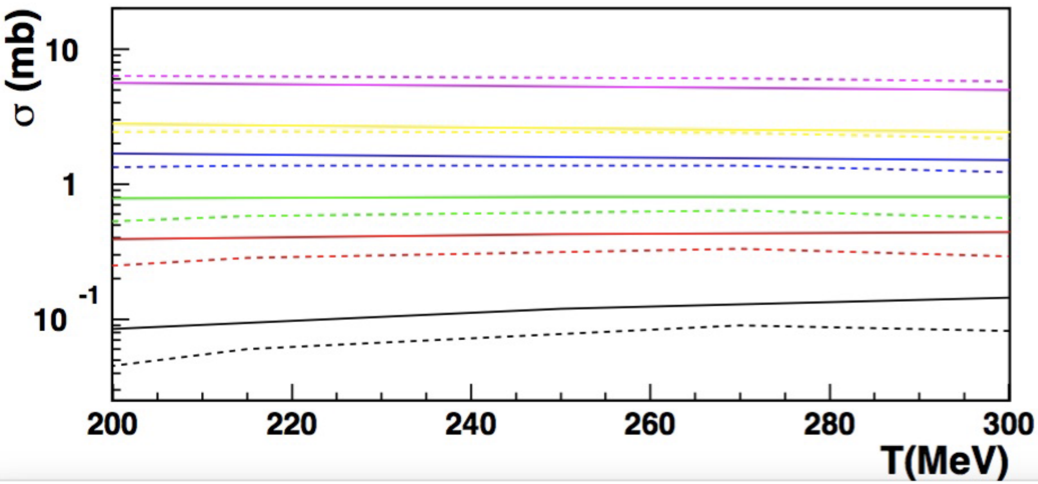


Using pPb CMS and ATLAS data at 5.02 TeV we fit T_{eff} and n. Also with PbPb CMS data

By varying n between 0.5 and 2, we obtain T_{eff} in the range from 200 to 300 MeV both for **partons** or **hadrons**

- High stability in the mentioned temperature range with running *n*



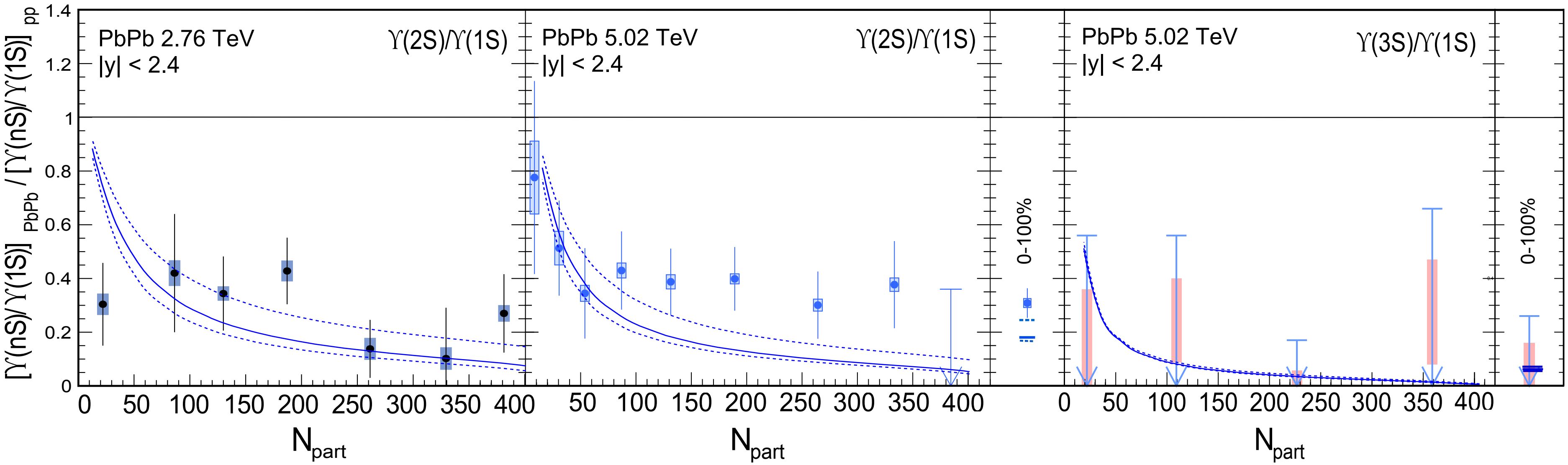
The mean values for the dissociation cross-sections for the bottomonium family in a comover medium made of pions (continuous line) or gluons (discontinuous line).
From down to up: 1S, 1P, 2S, 2P, 3S, 3P

Double ratio Υ(nS)/Υ(1S) in pPb & PbPb @ 2.76 & 5.02 TeV

For n=1 and T=250 ± 50 MeV:

Υ *p*Pb at 5.02 TeV

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



Υ(nS)/Υ(1S) well reproduced in PbPb collisions without any other phenomena needed

Consistency check: Υ(1S) nuclear modification factor in pPb

- Now that the $\sigma^{co-\mathcal{Q}_{b\bar{b}}}$ are fixed, we need to check the consistency with the absolute suppression of Υ(1S)

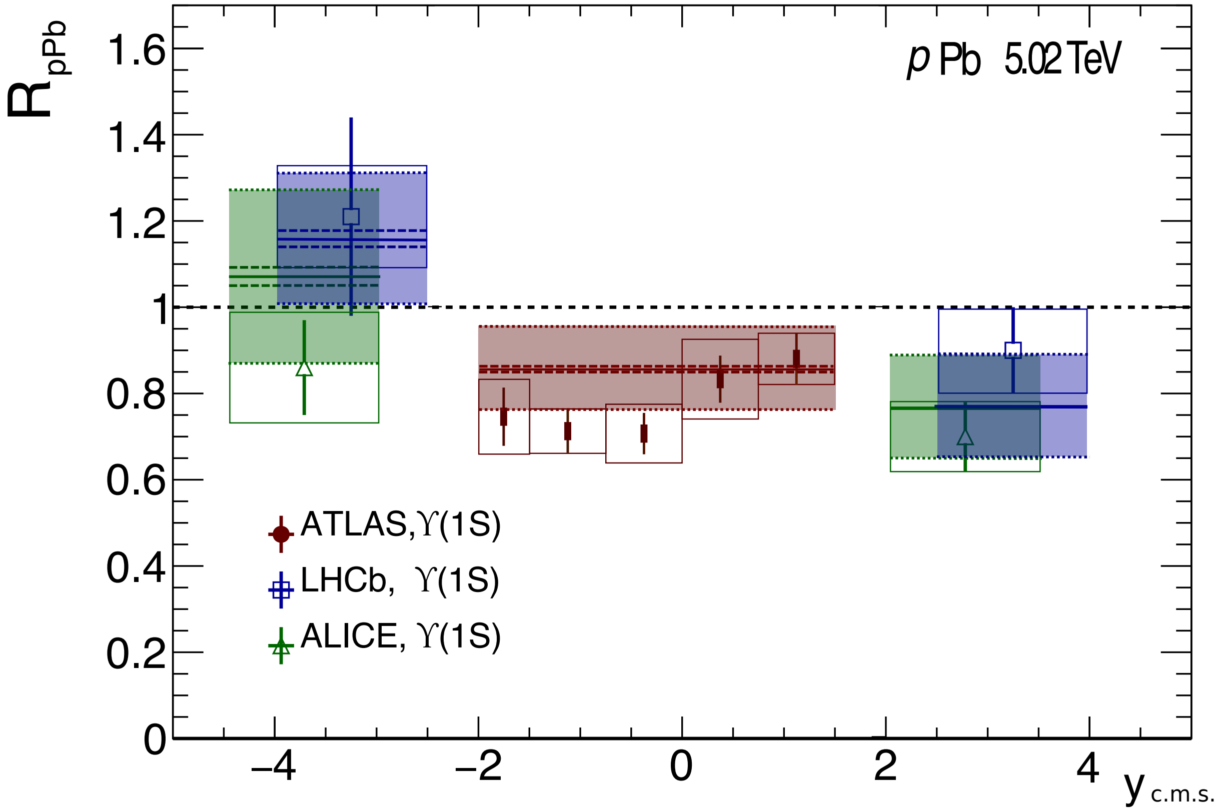
- Other nuclear effects which cancel in the double ratio, do not cancel anymore, i.e. shadowing

- We take into account nCTEQ15

- Comovers damp down the antishadowing peak

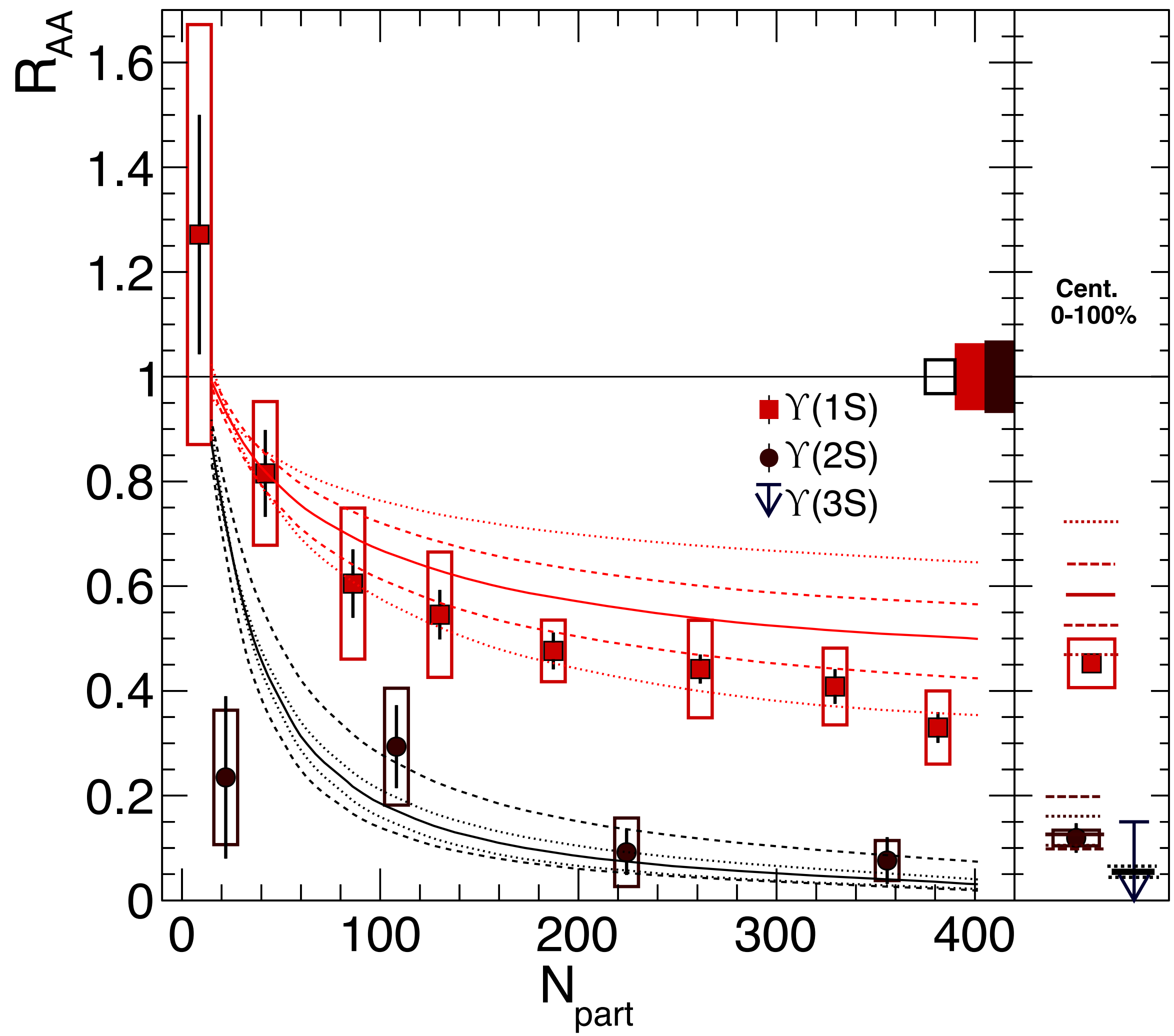
=> better agreement with ALICE

E. G. F., J.P. Lansberg, arXiv:1804.04474



Consistency check: R_{PbPb} for $\Upsilon(1S)$ and $\Upsilon(2S)$ @ 2.76 TeV

- We take into account nCTEQ15 (as for R_{pPb})
- We do show the **signicant uncertainty** of the barely known gluon nPDFs



The magnitude of suppression -taking into account nCTEQ15- is well reproduced without the need to invoke any other phenomena

Consistency check: R_{PbPb} for Υ(1S), Υ(2S) and Υ(3S) @ 5.02 TeV

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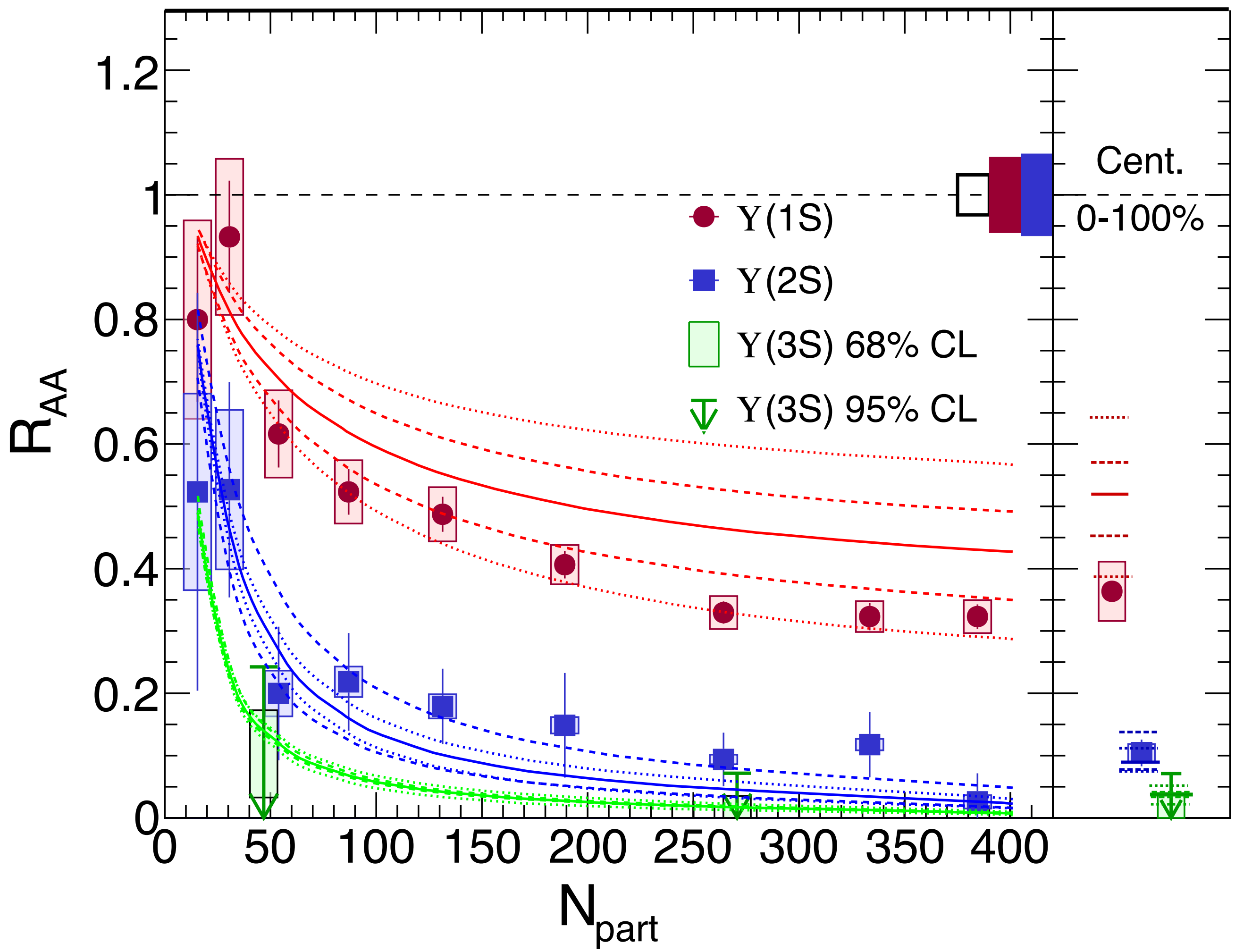

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Reaction rates (work in progress)

- In order to compare with other transport models, we are trying to obtain the temperature dependence of the inelastic reaction rate

- Let us convert our cross sections into dissociation widths $\Gamma^{Q} = \sigma^{\text{co}-Q}(E^{\text{co}};T)\,\rho^{\text{co}}.$

$$\Gamma^{Q}(E^{\text{co}},T) = \sigma^{\text{co}-Q}(E^{\text{co}})\,\frac{\rho^{\text{co}}}{e^{E^{\text{co}}/T}-1}$$

$$\Gamma^{Q}(T) = \int_{E^{Q}_{\text{thr}}}^{\infty} dE^{\text{co}}\,\sigma^{\text{co}-Q}(E^{\text{co}})\,\frac{\rho^{\text{co}}}{e^{E^{\text{co}}/T}-1}$$

$$\Gamma^{Q}(T) = \pi a_0^2 \int_{E^{Q}_{\text{thr}}}^{\infty} dE^{\text{co}} \left(1-\frac{E^{Q}_{\text{thr}}}{E^{\text{co}}}\right)^{n} \frac{\rho^{\text{co}}}{e^{E^{\text{co}}/T}-1}$$

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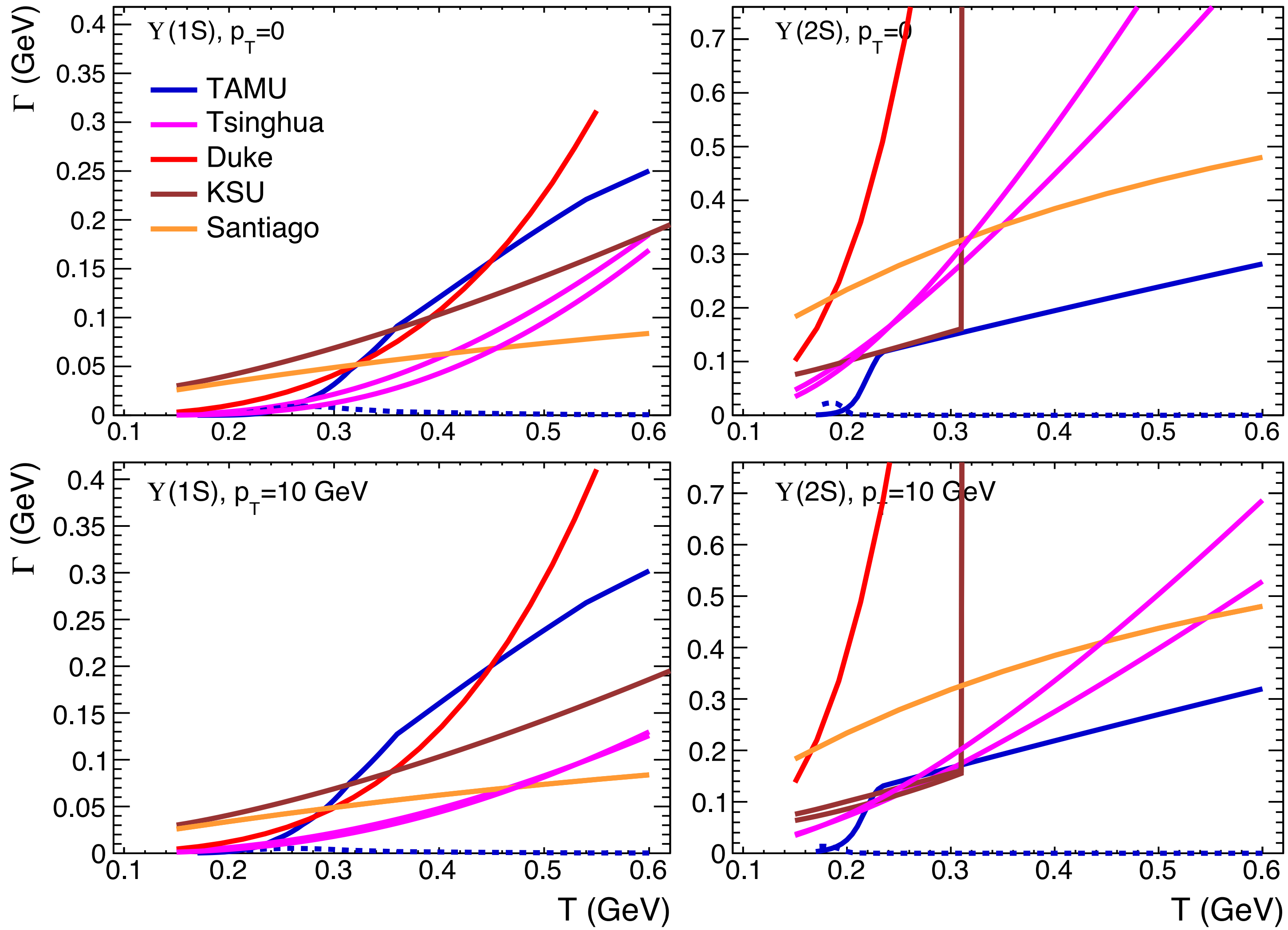

- Neither shadowing nor recombination included
- p_T integrated
- Formation time 0.3 fm

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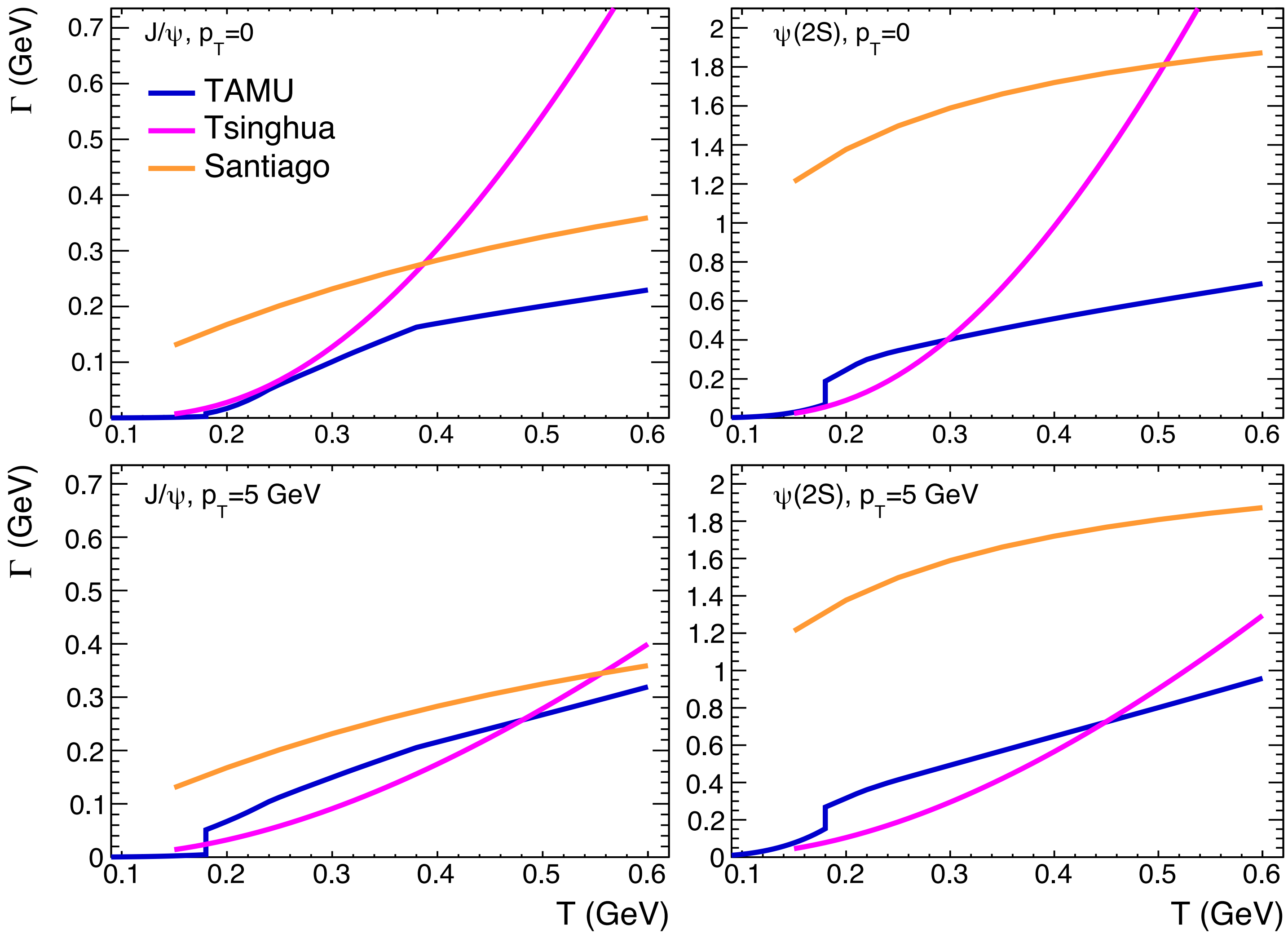

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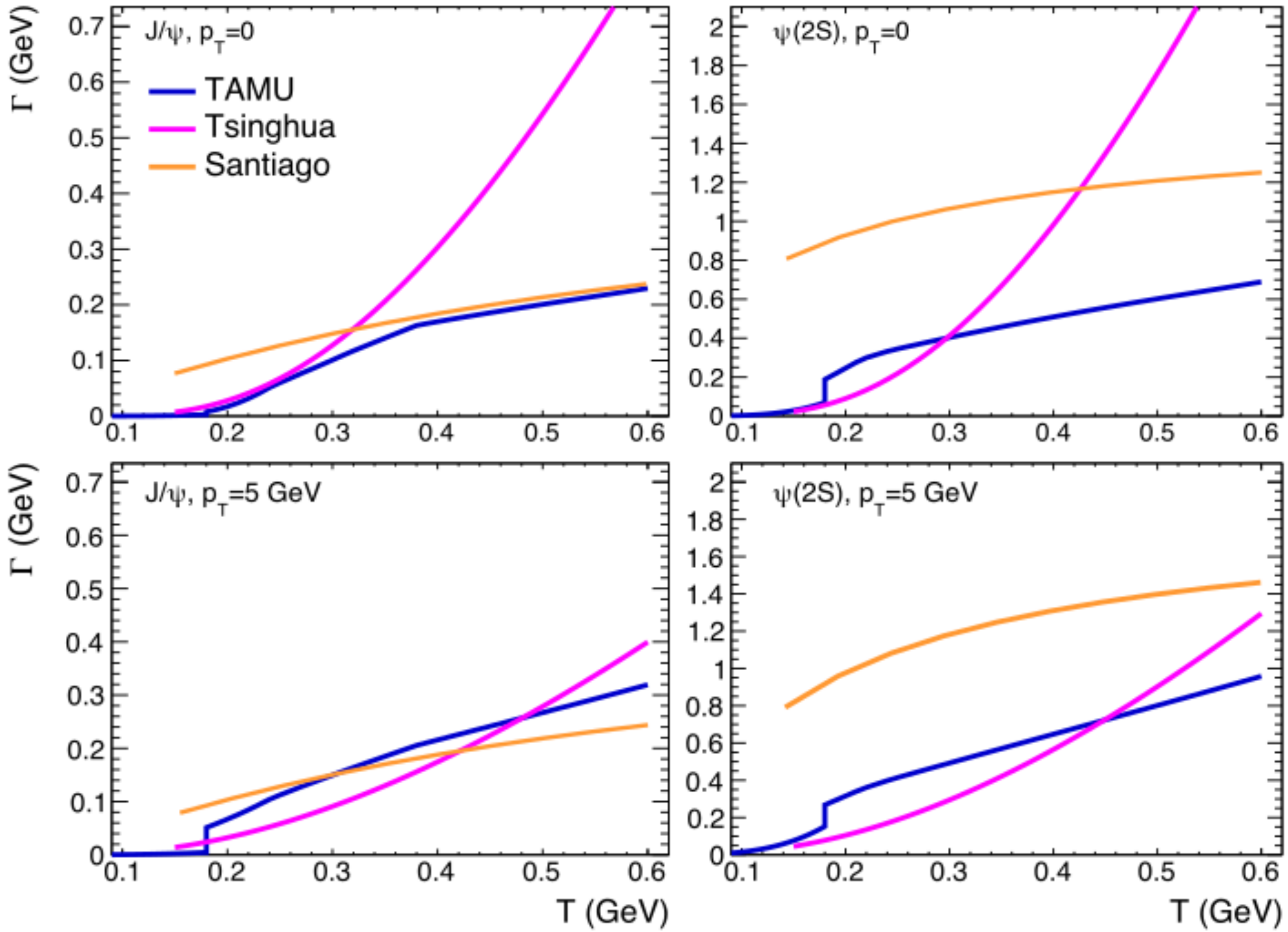

- Neither shadowing nor recombination included
- p_T integrated
- Formation time 0.45 fm

Physical interpretation: what the nature of the comovers is

- Case I: The medium is hadronic in pPb collisions, while it is gluonic in PbPb
  - The most common expectation: The relevant d.o.f. are hadrons in pPb collisions where the QGP is not produced whereas the gluons become relevant in the hotter PbPb environment with the presence of QGP

- Case II: Both in pPb and PbPb collisions, the medium is made of hadrons, i.e. the comovers can be identified with pions
  - Both in pA and AA collisions, Υ not affected by the hot (deconfined) medium
  - Possible interpretation: melting temperature of the Υ(1S) and Υ(2S) is too high to be observed and the Υ(3S) is fragile enough to be entirely broken by hadrons. Bottomonia unaffected by the presence of a possible QGP

- Case III: Both in pPb and PbPb collisions, the medium is made of partons, i.e. the comovers can be identified with gluons
  - Comovers are to be considered as partons in a (deconfined) medium
  - A QGP-like medium is formed following pPb collisions at LHC energies
  - CIM: effective modelling of bottomonium dissociation in the QGP