Extending the Satz & Matsui insight to the X(3872):

Sizing in-medium charmonia wave-functions

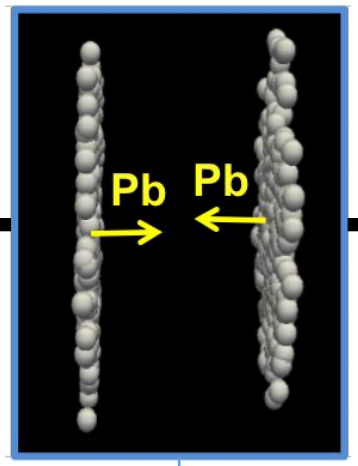
Henrique Legoinha, **Bernardo Picão**, Pedro Bicudo

Instituto Superior Técnico,

02/10/2026

Heavy Ion Collisions

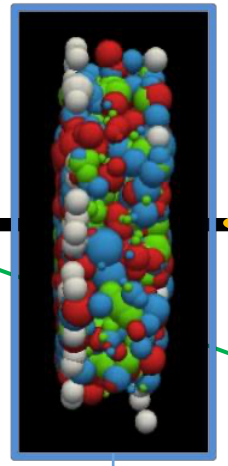
Pre-reaction



Nuclei are highly **contracted** at the collision moment!

Nuclei pictured by a **Color-Glass Condensate?**

QGP

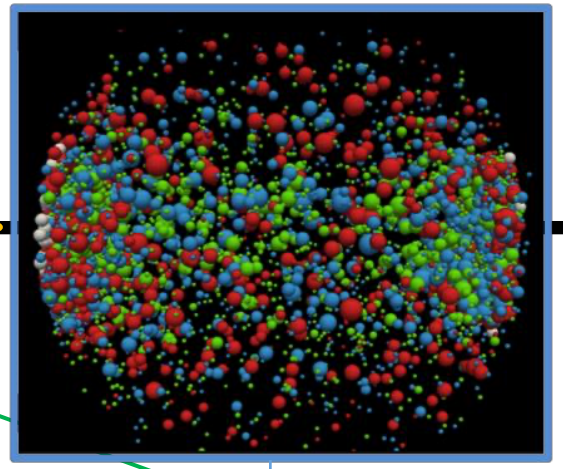


QGP droplets **form**! Chiral symmetry restored!

Can we **resolve quarks** and **gluons** ?

Transport properties of the medium ?

Hadronization

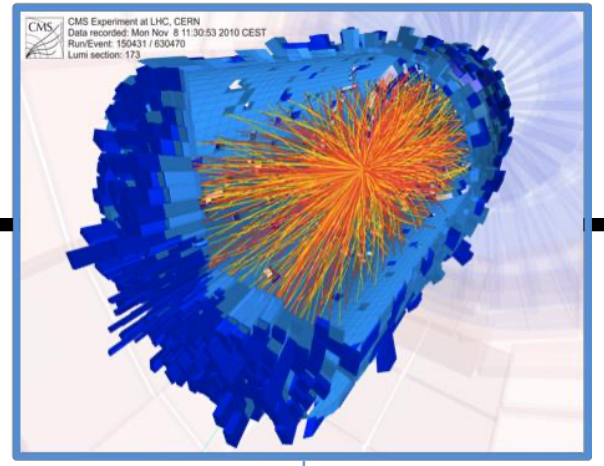


The **QGP shortly evaporates** into a mist of **hadrons!**

Hadronization is **non-pertubative**! how to **model/describe** it ?

What are the **QGP medium effects** on hadronization ?

Detection



Only the **remnants** of the **QGP** are **observable**!

Hard Probes

Soft Probes

Heavy flavour

Strangeness enhancement

Quarkonia

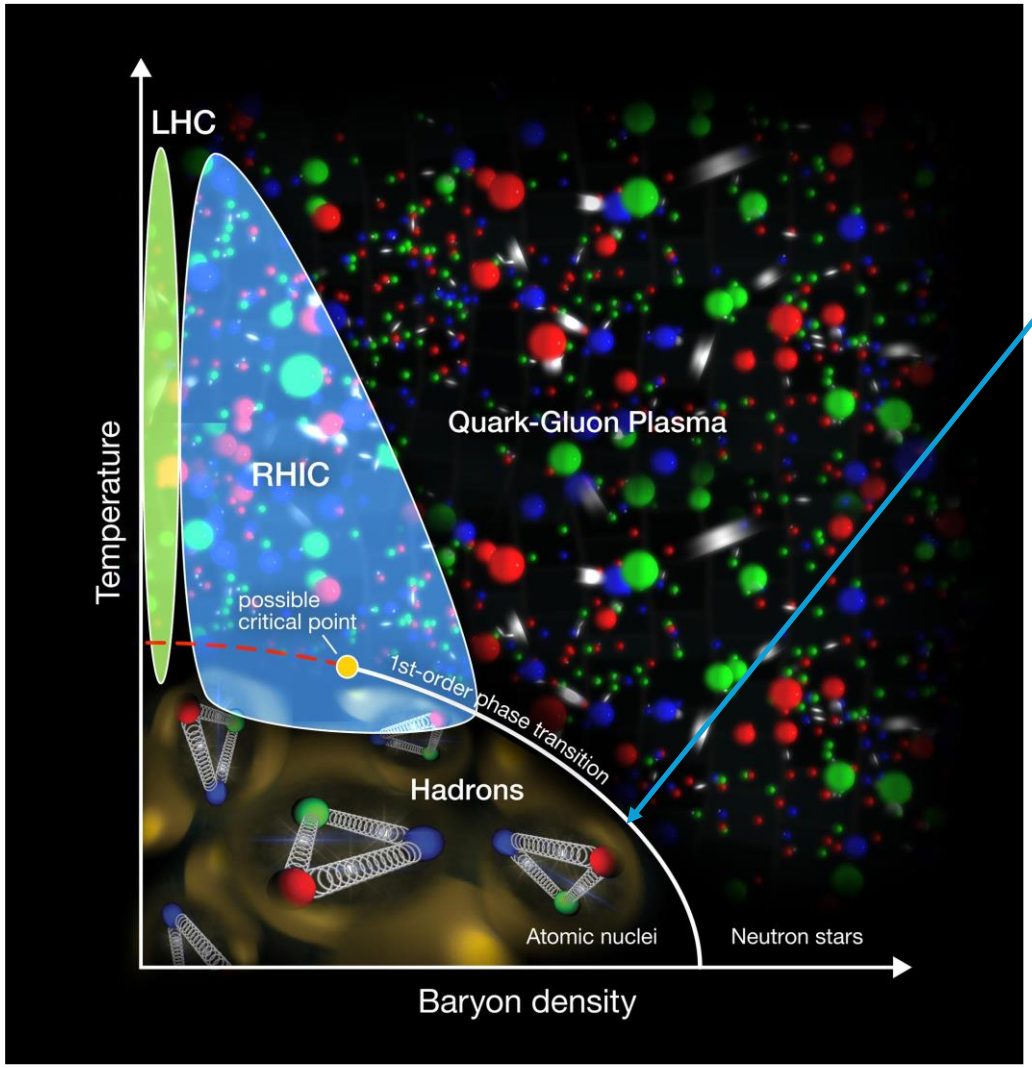
Elliptic flow

Jets

(Et al.)

Among other open questions…

The Quark-Gluon Plasma



Quantum-Chromodynamics predicts a **phase transition** where **hadrons "melt"** into their constituents.

The **transition** from **hadrons** into this **exotic state** reflects a fundamental **change** of the **QCD vacuum!**

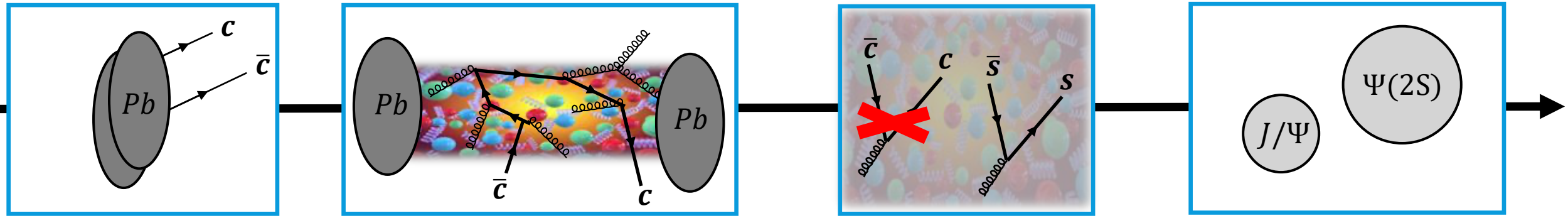
Quarks and **Gluons** form a **collective medium**

Quark-Gluon Plasma

behaving as near-perfect **relativistic fluid!**

Requires **extreme** conditions of **density** and **temperature** like the ones of the **early Universe...** or those at the core of **neutron stars...** and definitely those in **Heavy Ion Collisions!**

Quarkonia as QGP probes



Heavy quarks must be **produced in the initial hard scattering.**

Soft gluons saturate the **Color-Glass Condensate.**

Register medium effects while they traverse the QGP

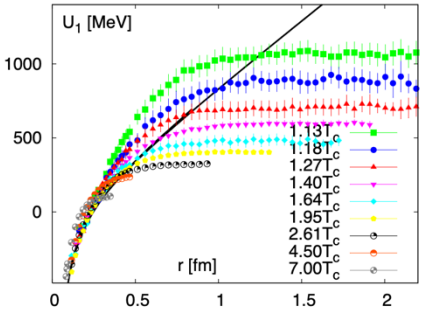
⬇

Great probes of the medium!
H. Satz, T. Matsui (1986)

Evolve according to **Brownian motion** or a **Lindbladian equation.**
(Complex hydrodynamics!)

Thermal production **not allowed**.

$c\bar{c}$ pairs **dissociate** due to **Debye screening** of the color charge and then can **recombine**.



O. Kaczmarek et al.

After **hadronization,** they can produce a clean dimuon signal.

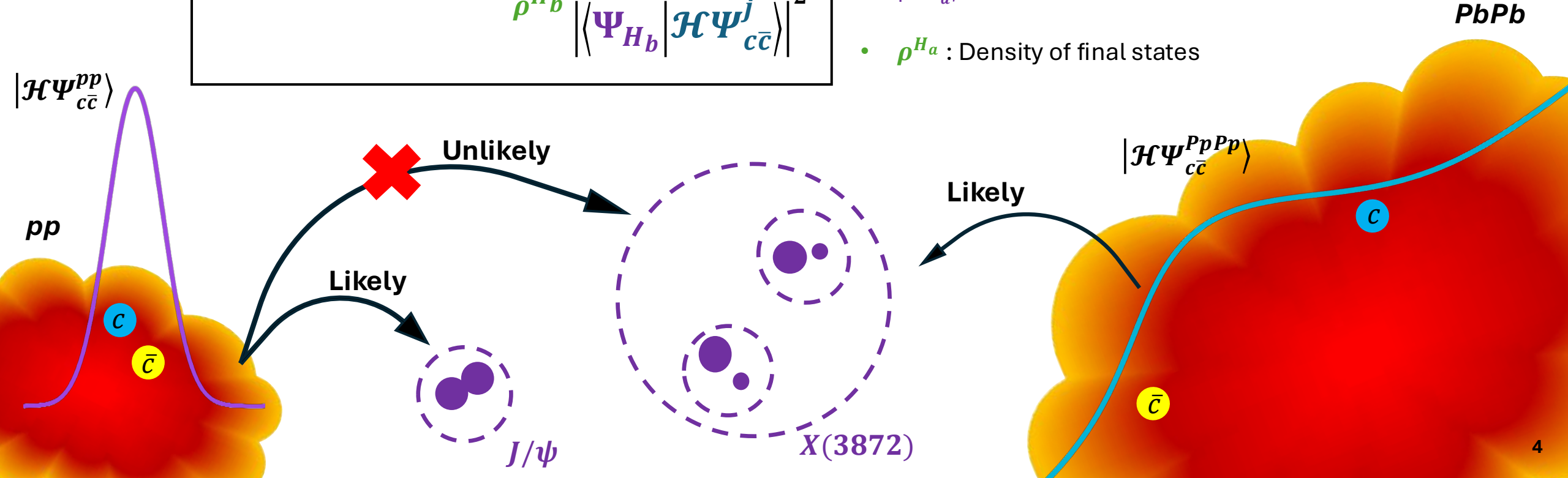
Further strong decays are suppressed by the **OZI rule.**

Hadronization from Fermi Golden Rule

We base ourselves in a **simple quantum mechanical concept**, namely the **overlap** of **Wave Functions,** and claim the observed **Hadron ratios** in ***pp*** and ***PbPb*** collisions are approximated? by the **Fermi Golden rule:**

$$\textbf{Hadron Ratios} \propto \frac{\rho^{Ha}}{\rho^{Hb}} \frac{\left|\left\langle \Psi_{H_a} \middle| \mathcal{H}\Psi^{i}_{c\bar{c}} \right\rangle\right|^2}{\left|\left\langle \Psi_{H_b} \middle| \mathcal{H}\Psi^{j}_{c\bar{c}} \right\rangle\right|^2}$$

- $\left|\mathcal{H}\Psi^{i}_{c\bar{c}}\right\rangle$: in-medium $c\bar{c}$ pair WF (i, j = systems)
- $\left|\Psi_{H_a}\right\rangle$: Hadron WF (H_a = J/ψ, $\psi(2S)$, etc)
- ρ^{H_a} : Density of final states



Left hand side of Golden Rule:

LHC Experiments

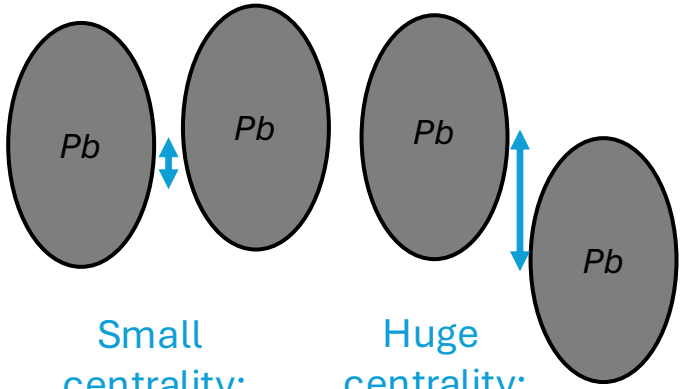
Hadron Ratios $\propto \frac{\rho^{H_a}}{\rho^{H_b}} \frac{\left|\left\langle \Psi_{H_a} \middle| \mathcal{H} \Psi^{i}_{c\bar{c}} \right\rangle\right|^2}{\left|\left\langle \Psi_{H_b} \middle| \mathcal{H} \Psi^{j}_{c\bar{c}} \right\rangle\right|^2}$

LHC experiments: strategy overview

Exp. Variables

- **Centrality** $(\boldsymbol{Cent})$

Collision off-set. Only available in PbPb. (A similar proxy is multiplicity and the number of participant nucleons)



Super relevant in Hin experiments!

- **Transverse momenta** $(\boldsymbol{p_T})$
- **Rapidity (y)**

Exp. Measurements

Differential measurements of **particle production** against $\boldsymbol{Cent}$ or ***multiplicty*** can highlight **system-size dependencies.**

$$d\sigma = \frac{dN/dCent}{\epsilon \mathcal{L} \mathcal{B}}$$

Differential measurements of **particle production** against $\boldsymbol{p_T}$ can probe different **QCD regimes.**

Measurements of relative **particle production,** namely **excited to ground state ratios,** capture **dynamic effects** from the **QGP**

$$R = \sigma^{\Psi(2S)} / \sigma^{J/\Psi}$$

$$DR = R^{PbPb} / R^{pp}$$

Comparison between **collision systems**, namely **pp vs PbPb**, further highlight **medium effects**

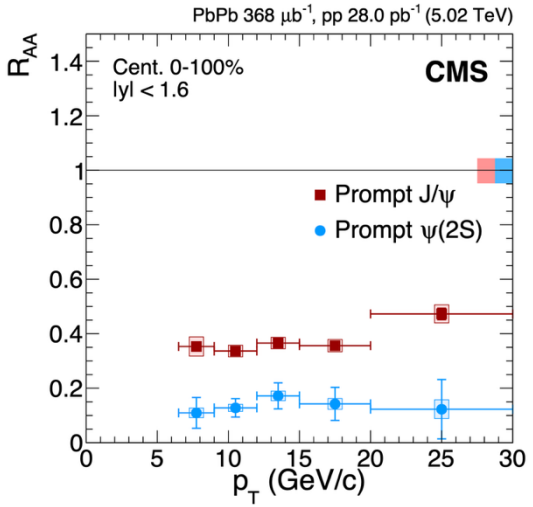
$$R_{\mathrm{AA}} = \frac{\mathrm{d}^2 N^{\mathrm{AA}} / (\mathrm{d}y \mathrm{d}p_{\mathrm{T}})}{\langle T_{\mathrm{AA}} \rangle \mathrm{d}^2 \sigma^{\mathrm{pp}} / (\mathrm{d}y \mathrm{d}p_{\mathrm{T}})}$$

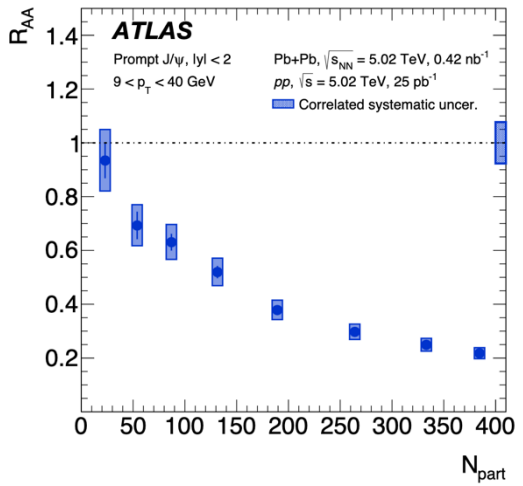
Interferometry measurements of equal bosons, namely pions, can tell the **size of particle-emitting sources**

etc

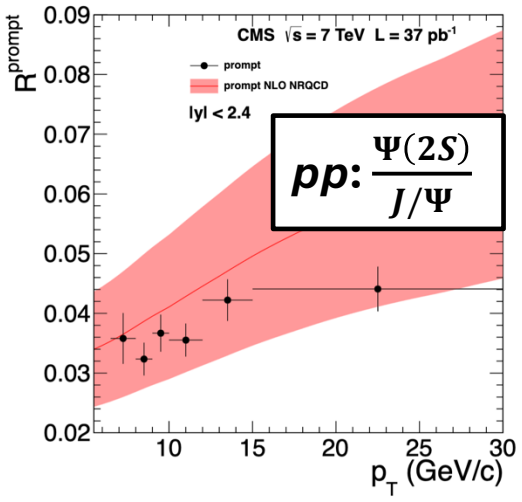
LHC experiments: Hadron Ratios

Nuclear Modification Factor

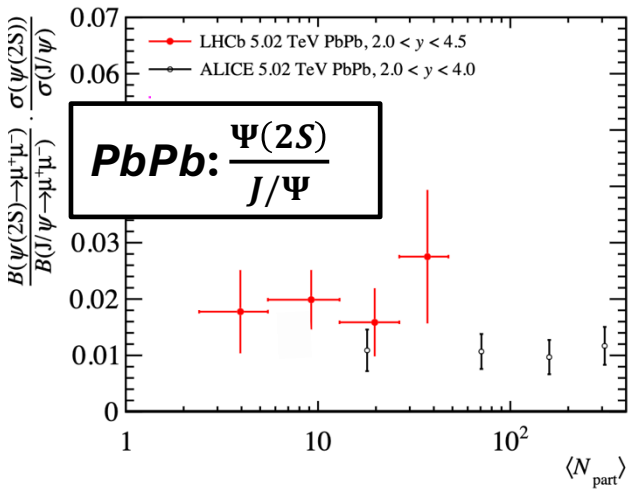




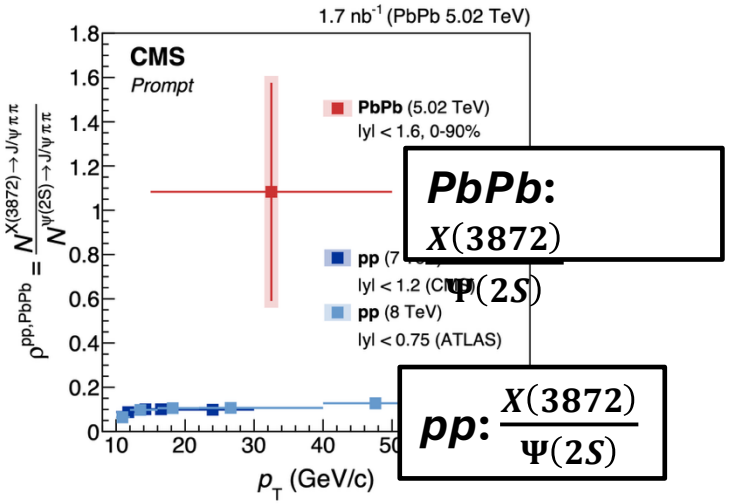
Relative Production



pp: $\frac{\Psi(2S)}{J/\Psi}$



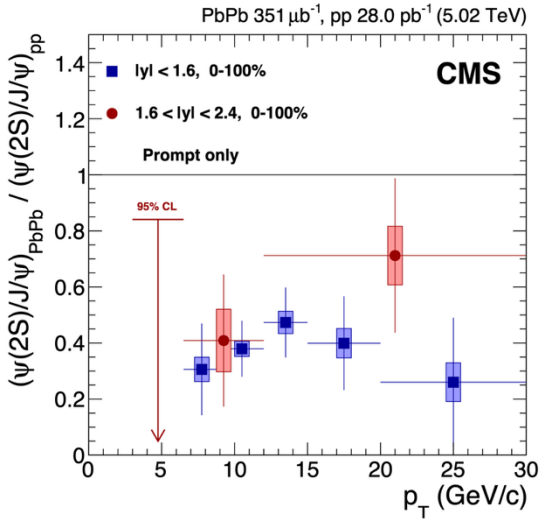
PbPb: $\frac{\Psi(2S)}{J/\Psi}$



PbPb: $X(3872)$ / $\Psi(2S)$

pp: $\frac{X(3872)}{\Psi(2S)}$

Double Ratio



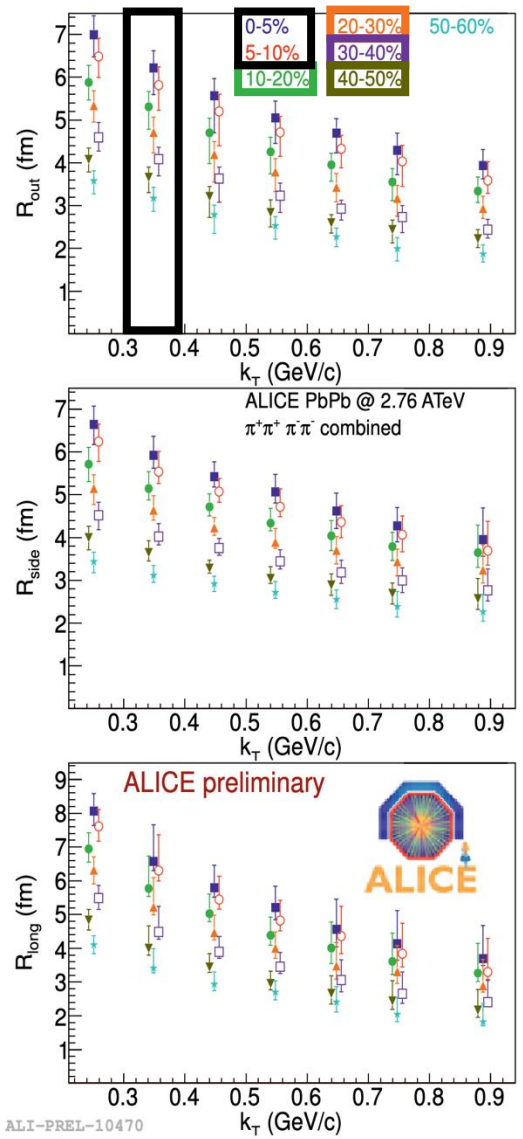
Consider the measurements compatible with

$p_T \sim 10\ GeV/c^2$

$y < 2.4$

To ensure consistency and proximity with the QGP thermal physics

LHC experiments: QGP medium size (R_{HBT})

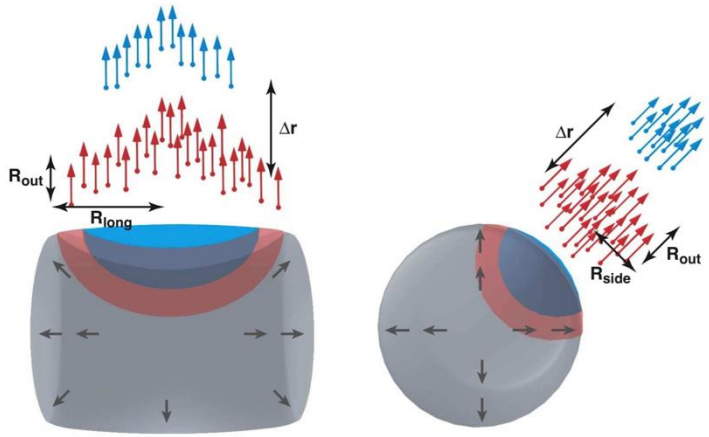


Hanbury Brown and Twiss (HBT) interferometry exploits the fact that particles emitted in quick succession from the same source are correlated.

The **bunching** (resp. antibunching) of bosons (resp. fermions), like pions or photons, with small relative momenta can thus be used to estimate the size of the source.

We use the geometric mean of the HBT radii as a proxy for the spatial extent of the QGP phase:

$R_{HBT} \approx 6\text{fm}$ for ***PbPb***,
$R_{HBT} \approx 1\text{fm}$ for ***pp***.



Credit: Annan Lisa et al.

Right hand side of Golden Rule:

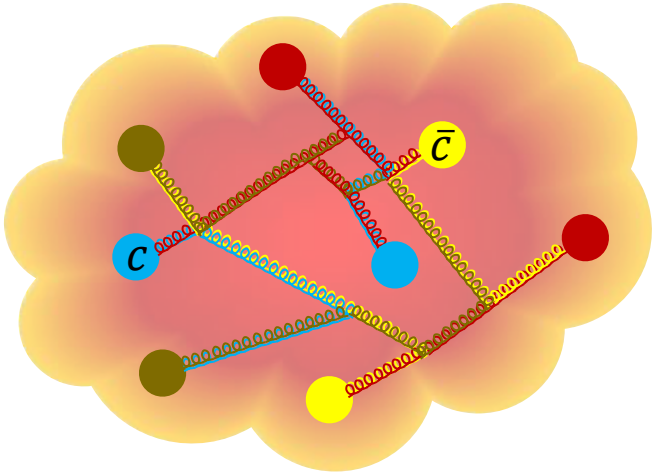
Wave Functions & Density of States

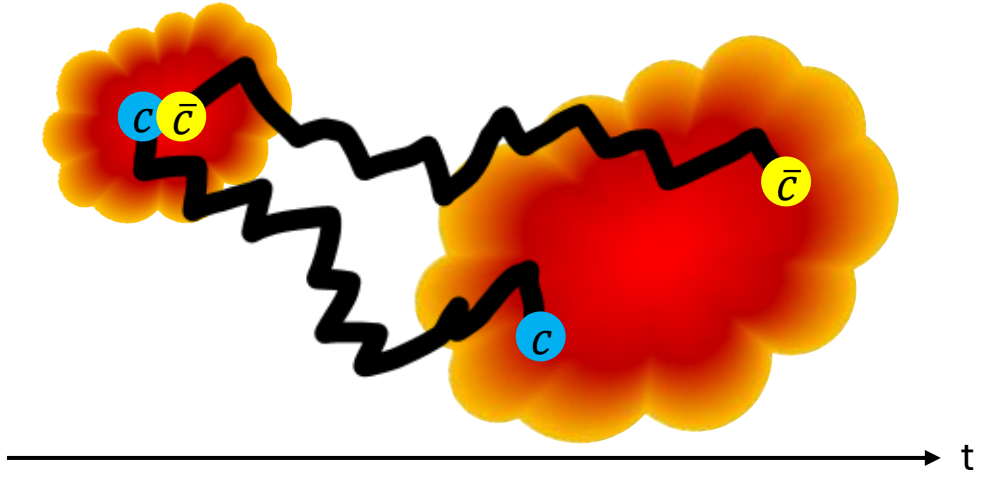
$$\text{Hadron Ratios} \propto \frac{\rho^{H_a}}{\rho^{H_b}} \frac{\left|\left\langle \Psi_{H_a} \middle| \mathcal{H} \Psi^{i}_{c\bar{c}} \right\rangle\right|^2}{\left|\left\langle \Psi_{H_b} \middle| \mathcal{H} \Psi^{j}_{c\bar{c}} \right\rangle\right|^2}$$

$c\bar{c}$ pair WF in the QGP

Medium's quarks and gluons **weaken** the **attraction** between the $c\bar{c}$ pair

Charm quarks undergo **Brownian motion** while moving in the QGP





A Gaussian function can capture these **random effects** well:

Gaussian: $\Psi^{pp}(r)_{c\bar{c}} = N\, Gau(\sigma_1; r)$

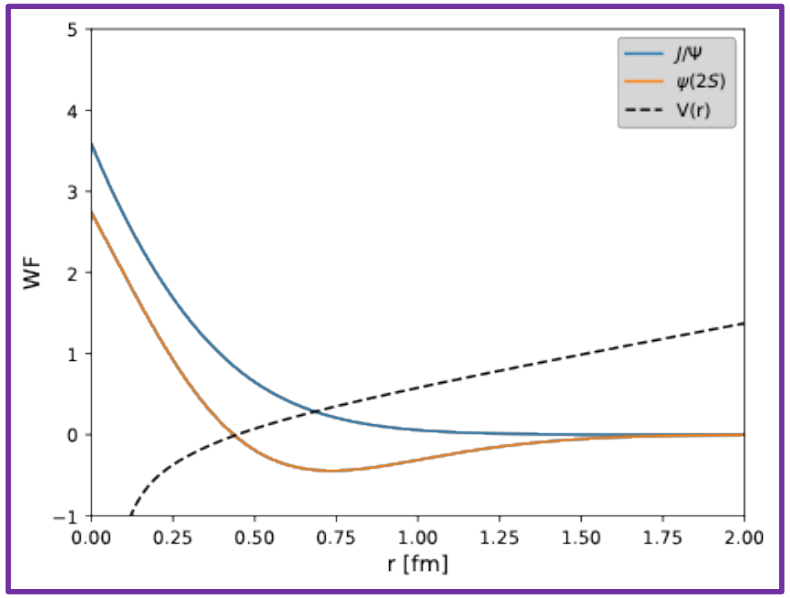
In the ***PbPb* system**, we include a **second gaussian,** to better accommodate **intensive QGP effects**:

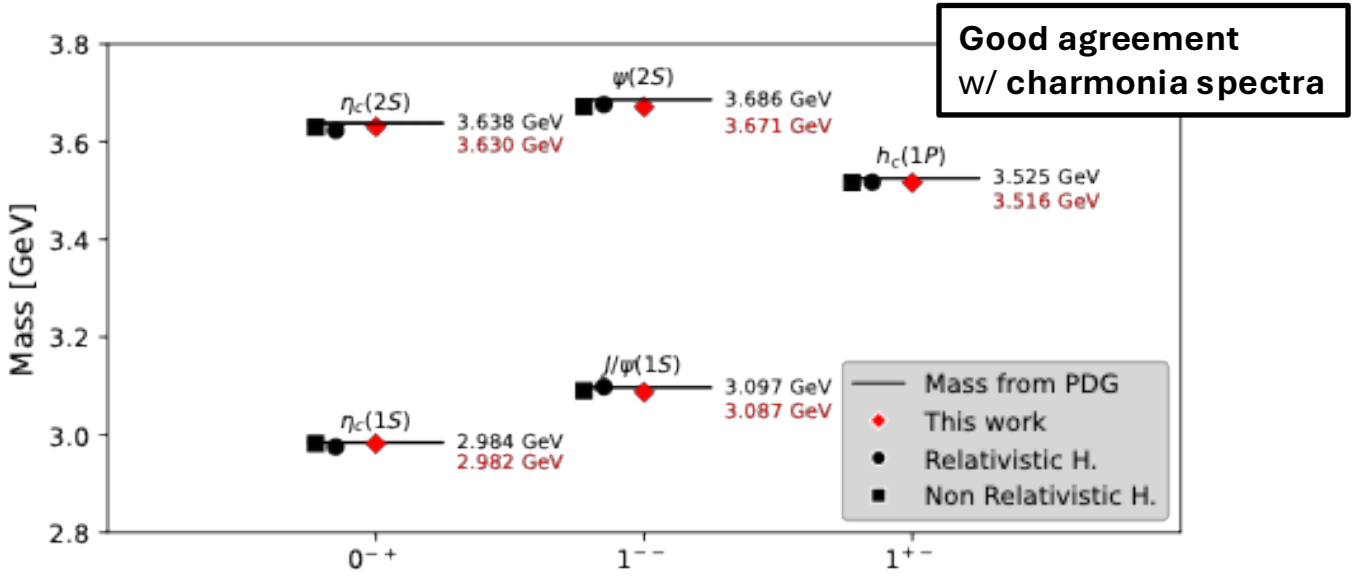
Double Gaussian: $\Psi^{PbPb}(r)_{c\bar{c}} = N[\sqrt{\alpha}\, Gau(\sigma_2; r) + \sqrt{1-\alpha}\, Gau(R_{HBT}; r)]$

Solving Sch. Equation for $|J/\psi\rangle$ and $|\psi(2S)\rangle$

We solve coupled channel Sch. Equation for the potential given in T.Barnes, S.Godfrey, E.S.Swanson :

$$H_{c\bar{c}} = \frac{p^2}{2m_{red}} - \frac{4\alpha_s}{3r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}(r)\vec{S}_c \cdot \vec{S}_{\bar{c}} + \frac{1}{m_c^2}\left[\left(\frac{2\alpha_S}{r^3} - \frac{b}{2r}\right)\vec{L} \cdot \vec{S} + \frac{4\alpha_s}{r^3}T\right]$$





To account for $1/r^3$ terms we introduce a smearing dependent on the quark mass $r^3 \to (r^2 + m_c^2)^{3/2}$

Wave Function for X(3872)

From **Low Energy Universality (LEU)** [E. Braaten, M. Kusonoki] there is a prediction for the **WF of shallow states** like the $X(3872)$:

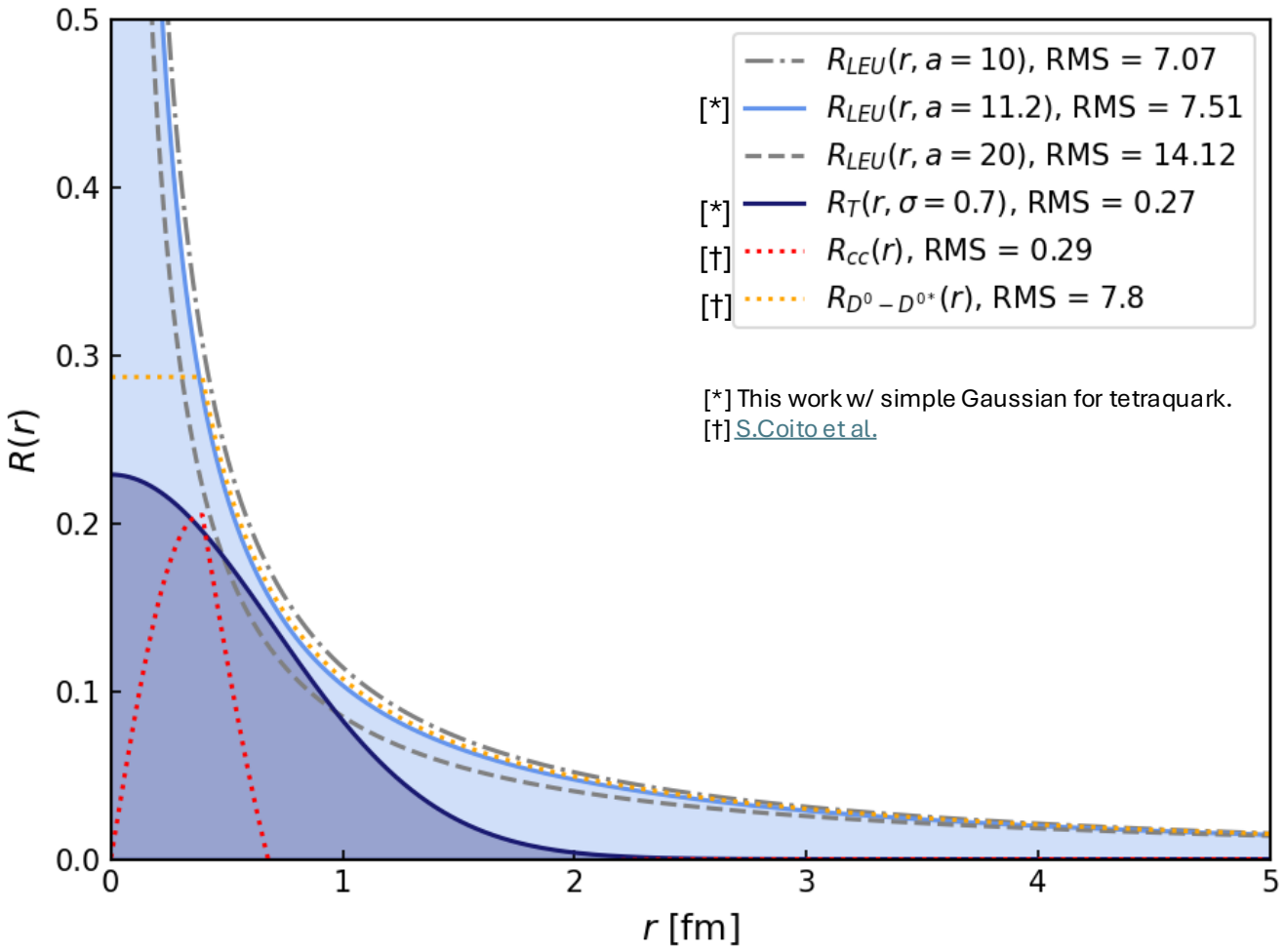
$$\boldsymbol{R(r)^{LEU} = \frac{1}{r\sqrt{(2\pi a)}} exp(-r/a)}$$

Suggesting it is a $\boldsymbol{D^0 - \bar{D}^{0*}}$ **meson molecule**. However, **mixing** with:

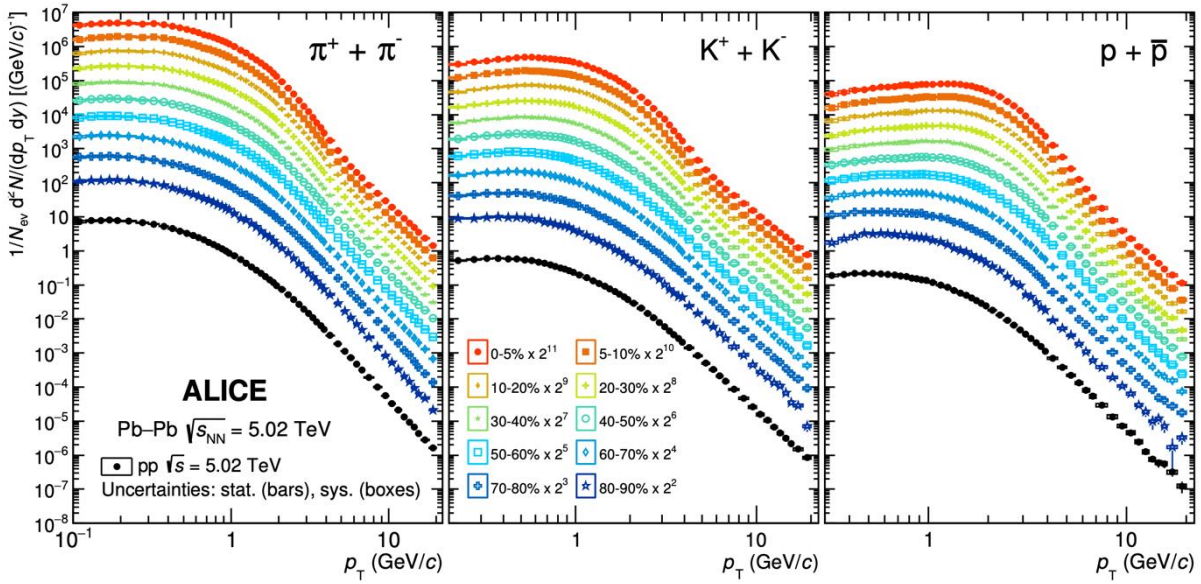
(i) Tetraquark ($\boldsymbol{c\bar{c}\bar{q}q}$) [*]
(ii) Charmonia ($\boldsymbol{c\bar{c}}$) [†]

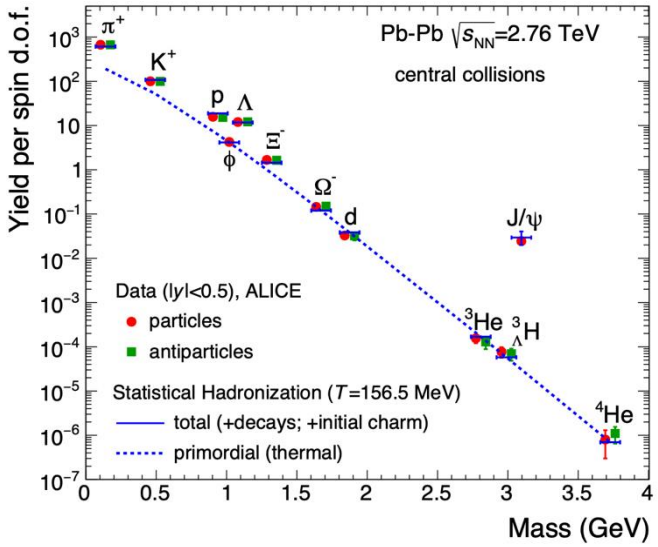
will occur, with the molecule dominating others at **~90%.** Therefore, we build a simple model incorporating mixing with a tetraquark state:

$$\Psi_{X(3872)} = \sqrt{0.1}\ Gau(0.7; r) + \sqrt{0.9}\ \Psi^{LEU}(r)$$



Density of States





A. Andronic et al. (2019)

For the density of states of the resulting hadrons, we use a simple ansatz of a Lorentz-invariant phase space with a Boltzmann factor:

$$\rho \sim \int \frac{d^3p}{(2\pi)^3 2E} \exp\left(-\frac{E}{T}\right)$$

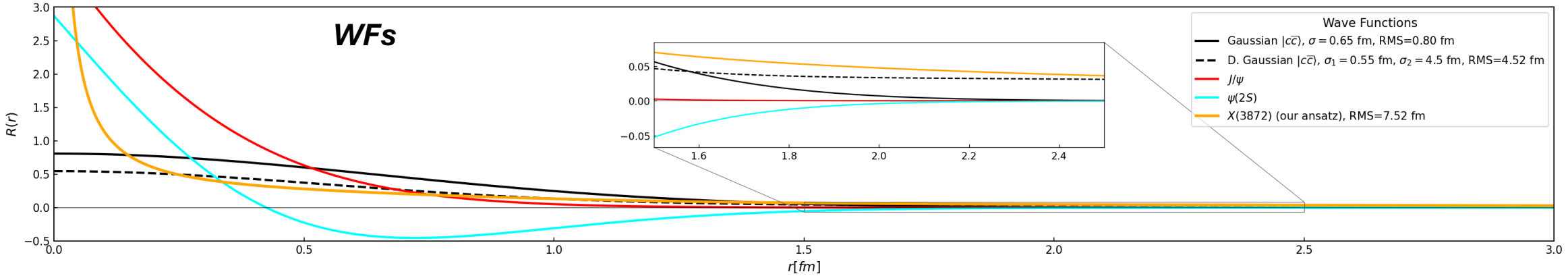
with the temperature at $T = 156.5MeV$ according to the Statistical Hadronization Model.

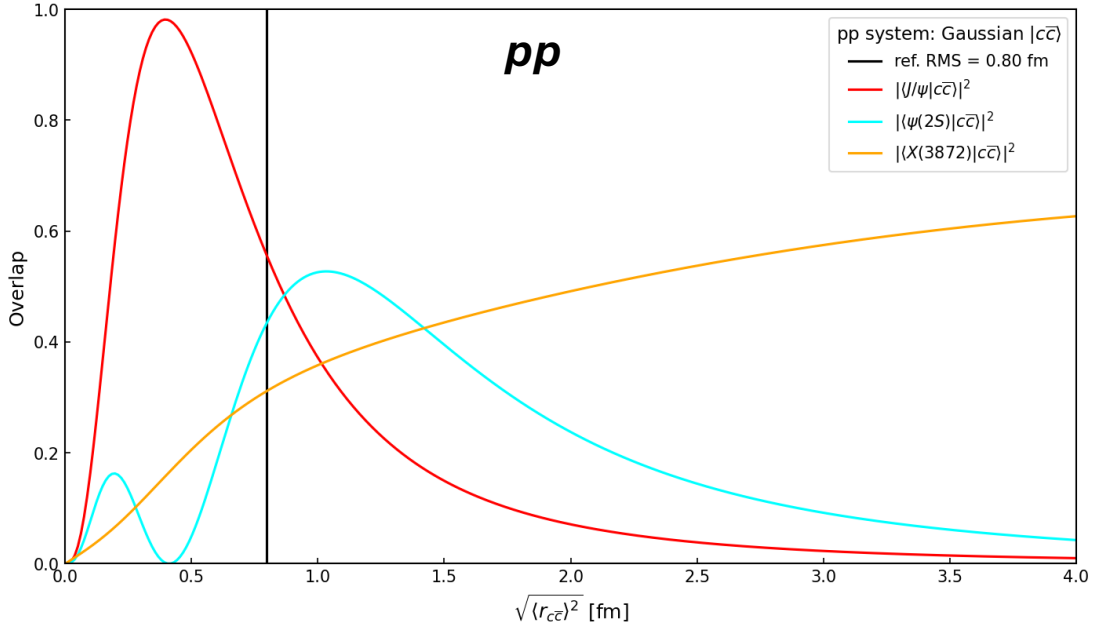
Performing the change of variables to transverse momentum and rapidity:

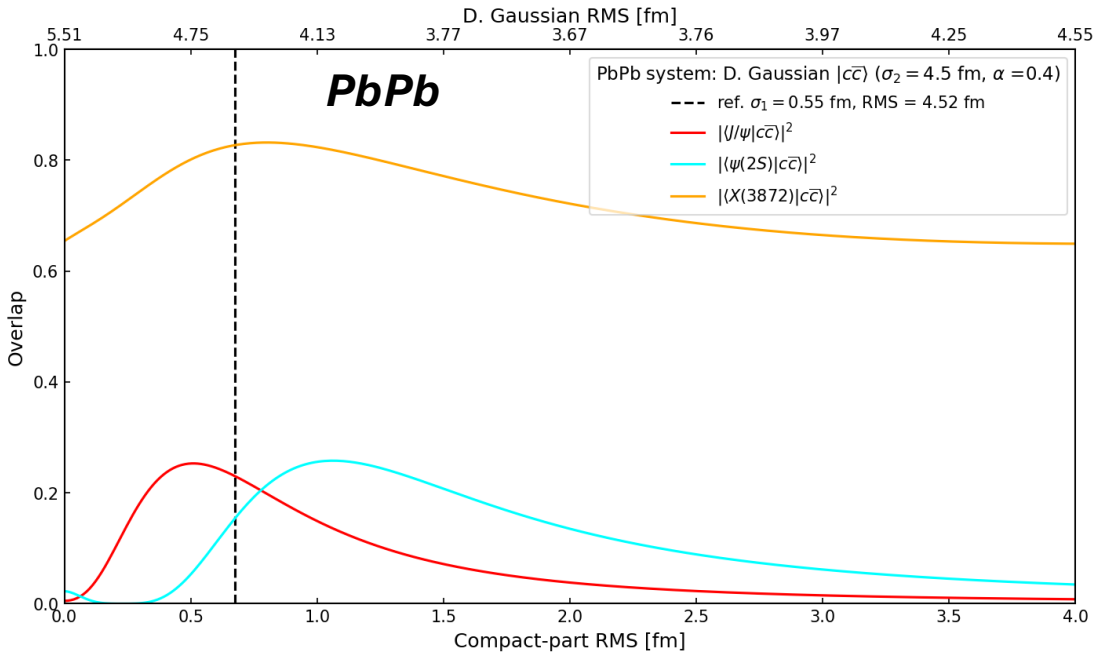
$$E = m_T \cosh(y) \quad \text{with} \quad m_T = \sqrt{{p_T}^2 + M_H^2},$$

one can perform the integral numerically in the relevant kinematic region.

Charm pair inner products $|\langle \Psi_{H_a} | \mathcal{H} \Psi^i_{c\bar{c}} \rangle|^2$

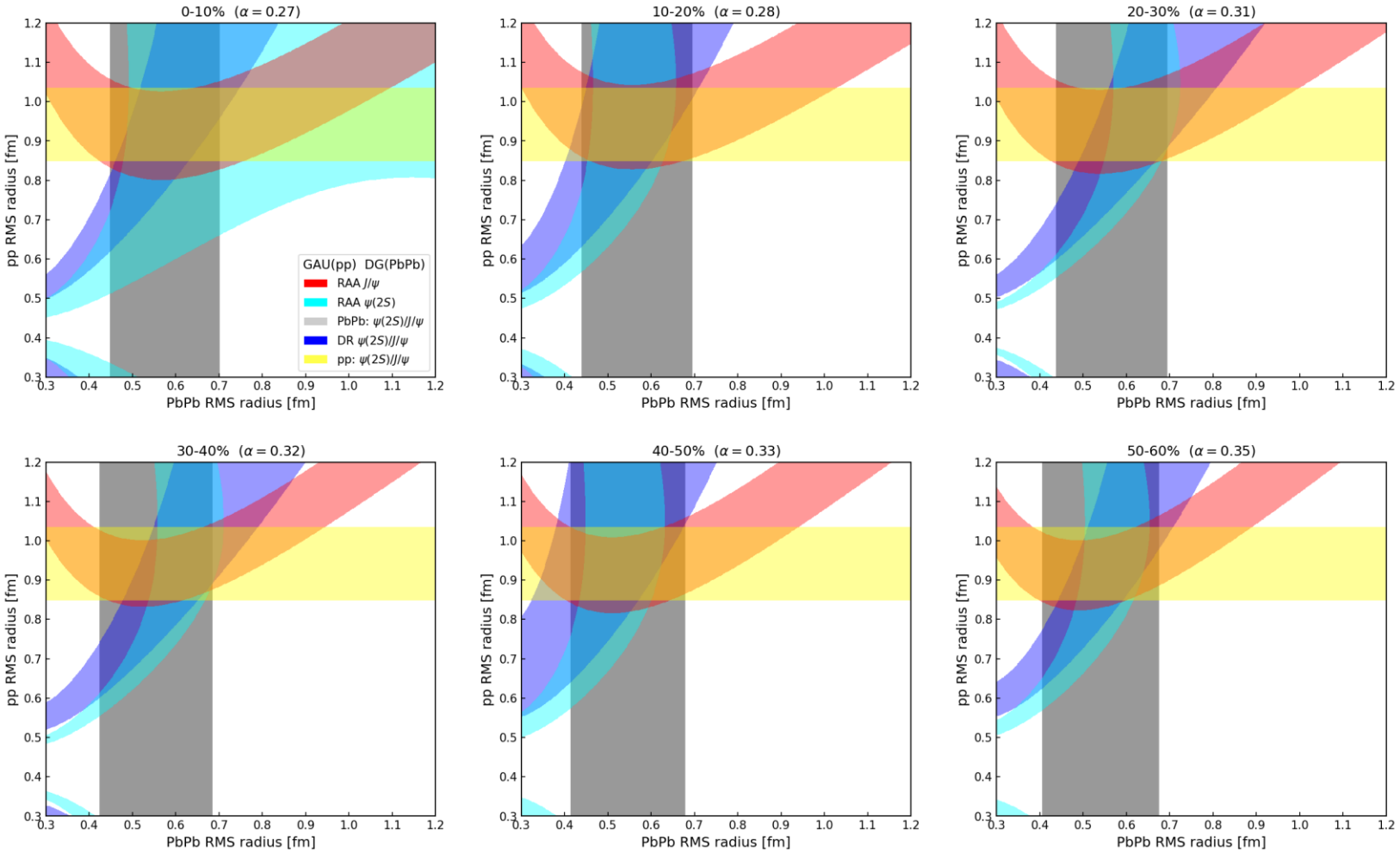






What we find: Hidden-Charm vs Centrality

$\Psi^{pp}(\sigma_1)_{c\bar{c}} = N\,Gau(\sigma_1; r)$

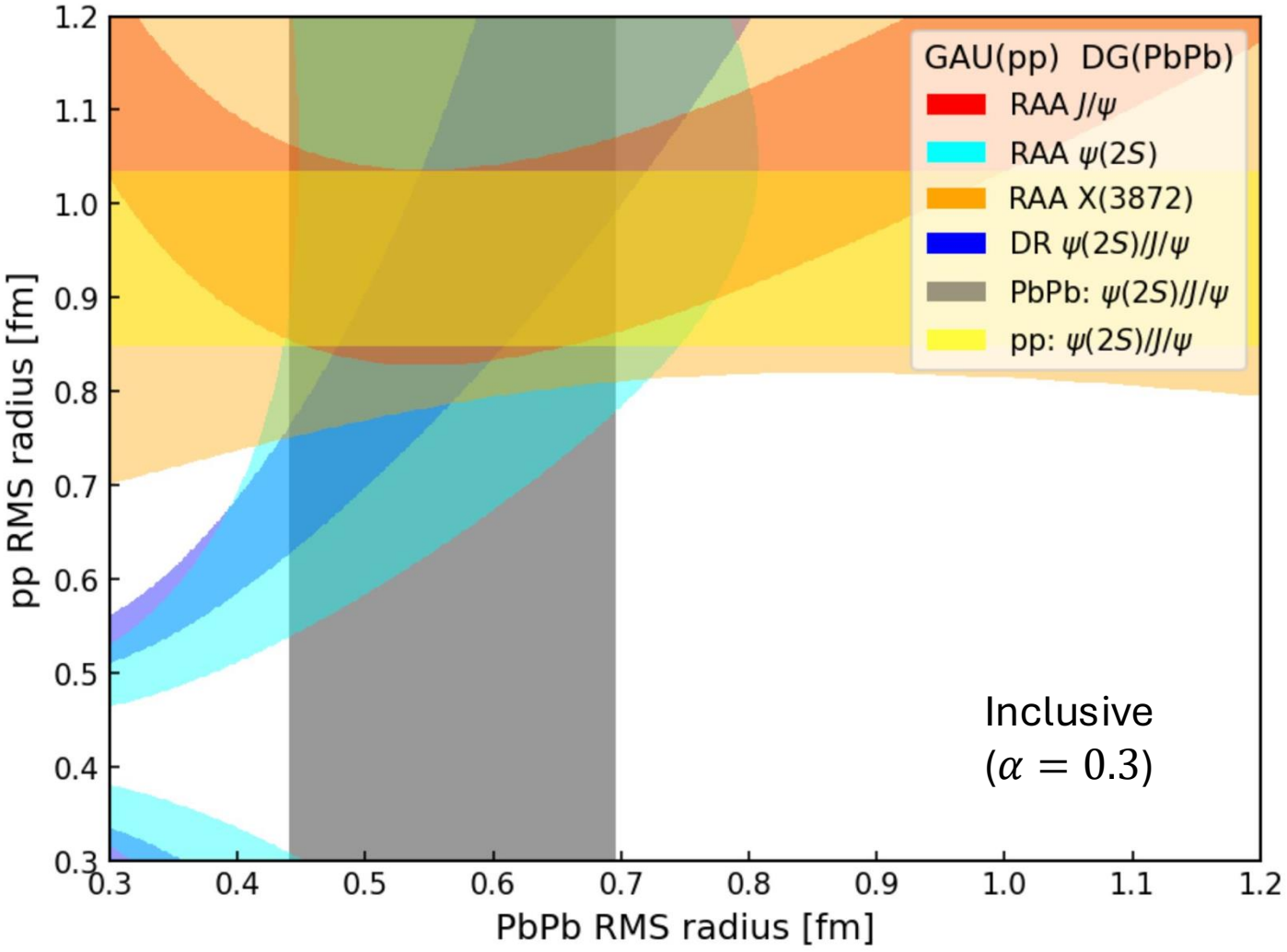


- The bands show the ***RMS*** values of the respective ***pp*** and ***PbPb*** gaussians that **reproduce measured hadron ratios**.
  - ✓ There are **consistent overlaps** at
    ~ 0.85 fm in ***pp***
    ~ 0.55 fm in ***PbPb***
    thus respecting hadronic scale.
- As **centrality increases** the **compact part** $\boldsymbol{\alpha}$ gets more **suppressed**.
  - ✓ Expected since **central collisions** yield a **more robust QGP.**
- Charmonia ratios are more **sensitive** to the **fraction** $\boldsymbol{\alpha}$ than to the **size** of the broad gaussian (R_{HBT}).
  - ✓ Expected since **charmonia** are **compact** and so do **not couple** well to **"flat" WFs**.

$$\Psi^{PbPb}(\sigma_1, \alpha)_{c\bar{c}} = N[\sqrt{\alpha}\ Gau(\sigma_1; r)\ +\ \sqrt{1-\alpha}\ Gau(R_{HBT}; r)]$$

What we find: including X(3872)

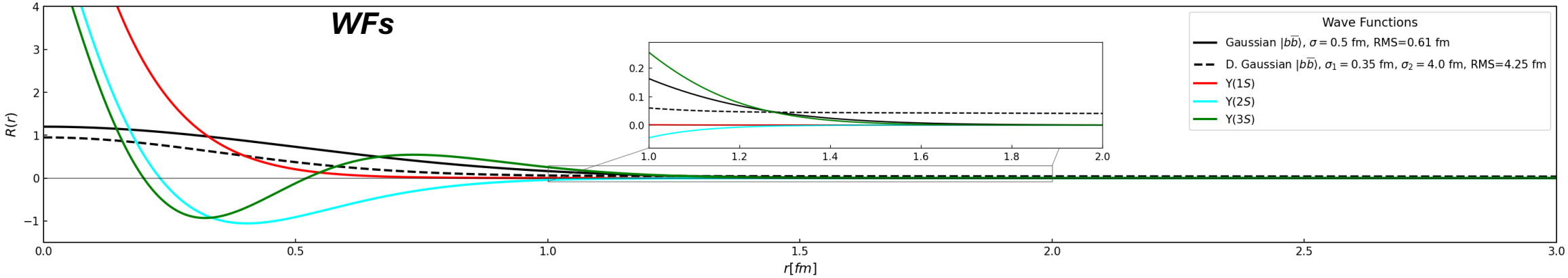
$\Psi^{pp}(\sigma_1)_{c\bar{c}} = N\,Gau(\sigma_1; r)$

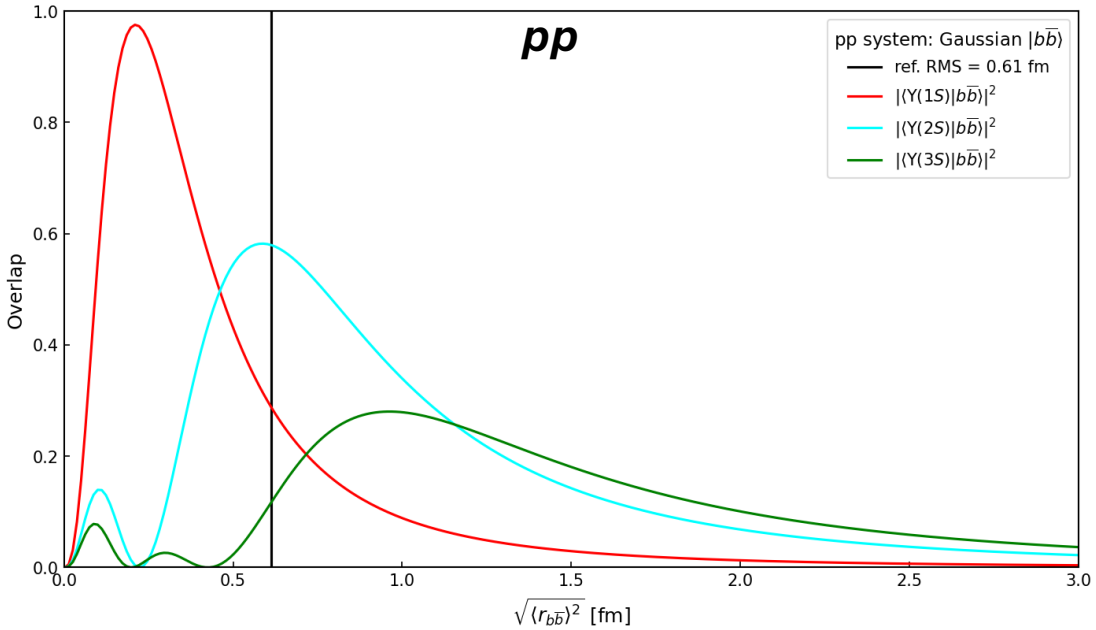


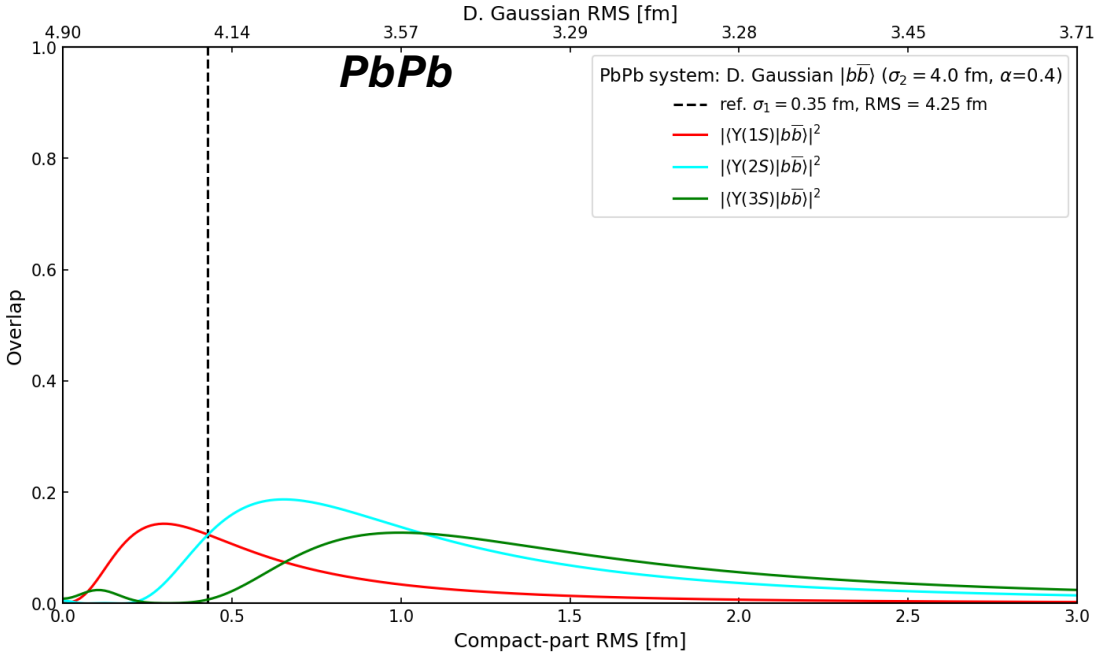
$$\Psi^{PbPb}(\sigma_1, \alpha)_{c\bar{c}} = N[\sqrt{\alpha}\ Gau(\sigma_1; r)\ +\ \sqrt{1-\alpha}\ Gau(R_{HBT}; r)]$$

- Including the X(3872), we can see the overlap is maintained.
  - ✓ Provides further confirmation that the X(3872) admixture is mostly **dominated by a large meson-meson component**.
- Gaussian component **couples** to the compact charmonium and is **essential** for the presence overlap.
  - ✓ Validates the presence of a **compact component** in the X(3872).
- The absence of X(3872) production in ***pp*** collisions can be explained by the **small overlap** with the highly localized $\boldsymbol{c\bar{c}}$ wf.

Bottom Inner products $|\langle \Psi_{H_a} | \mathcal{H} \Psi^{i}_{\bar{b}b} \rangle|^2$

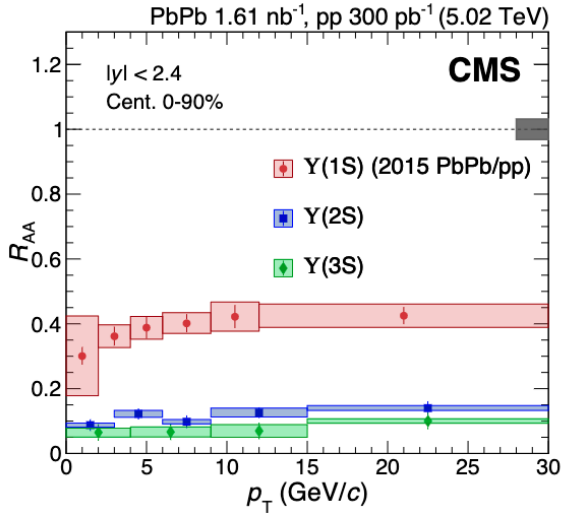


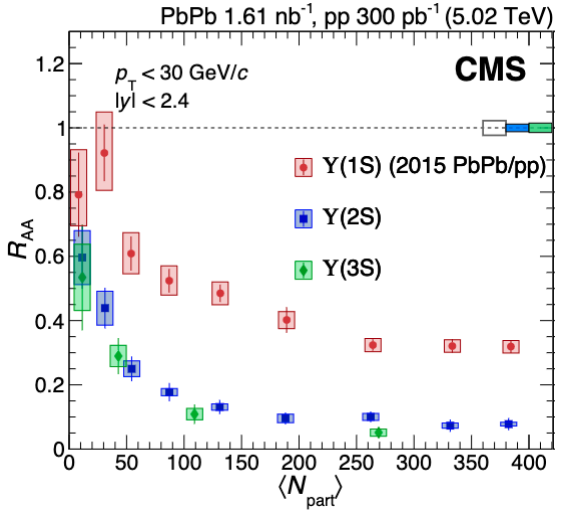




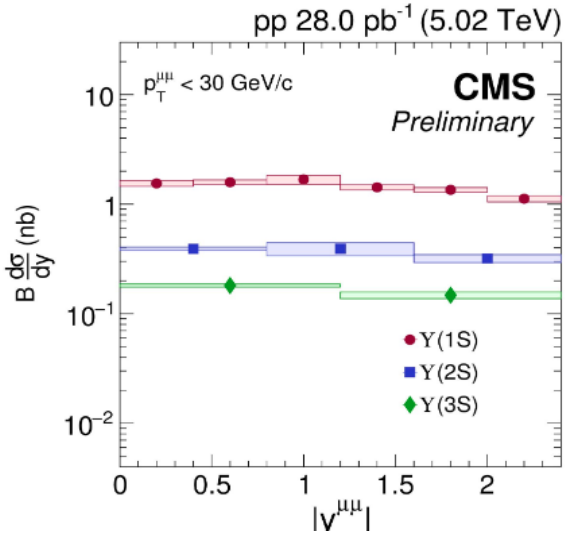
LHC experiments: Bottomonia

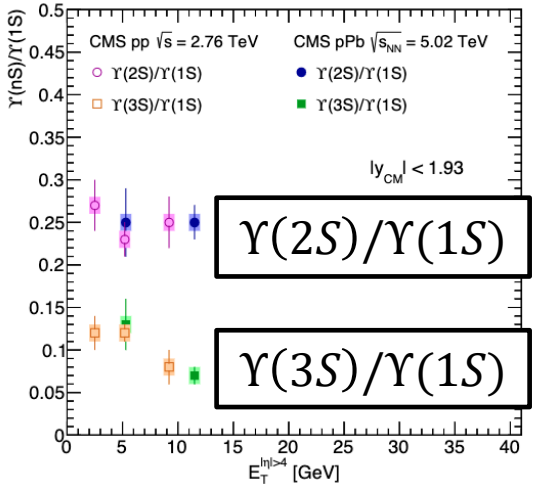
Nuclear Modification Factor



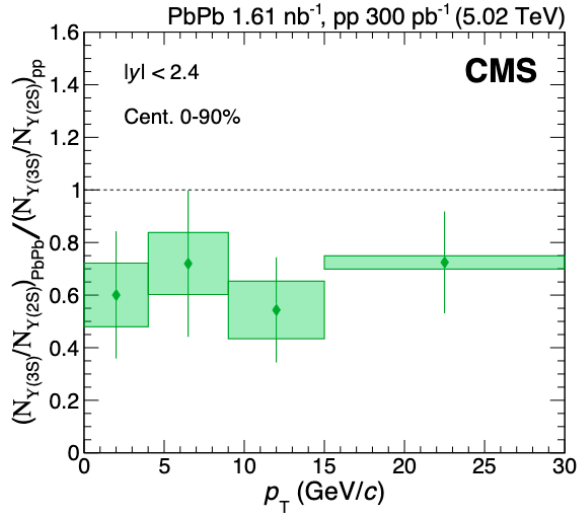


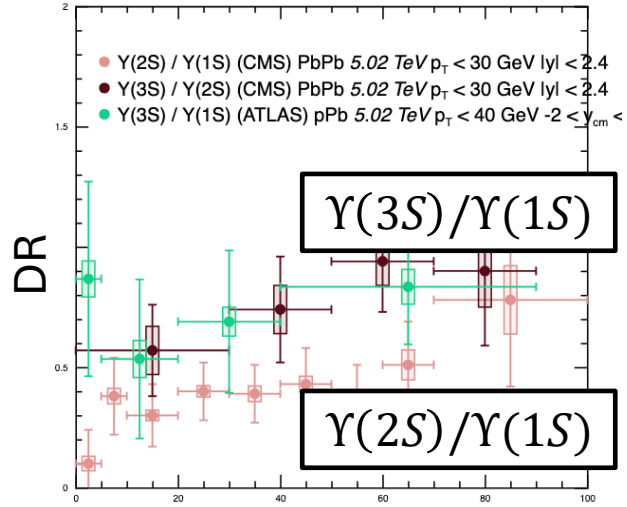
Relative Production

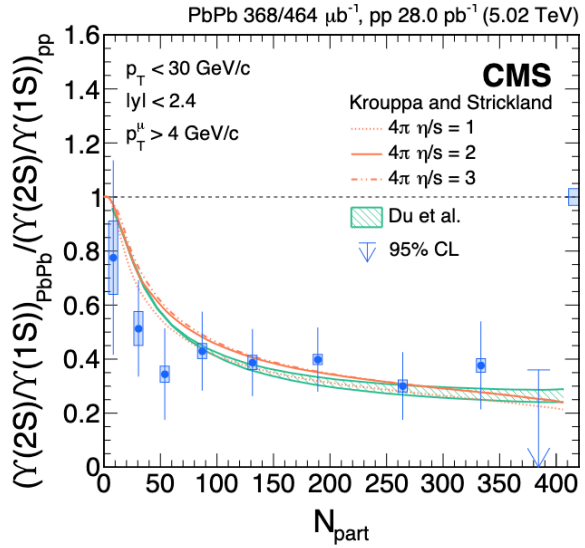




Double ratio

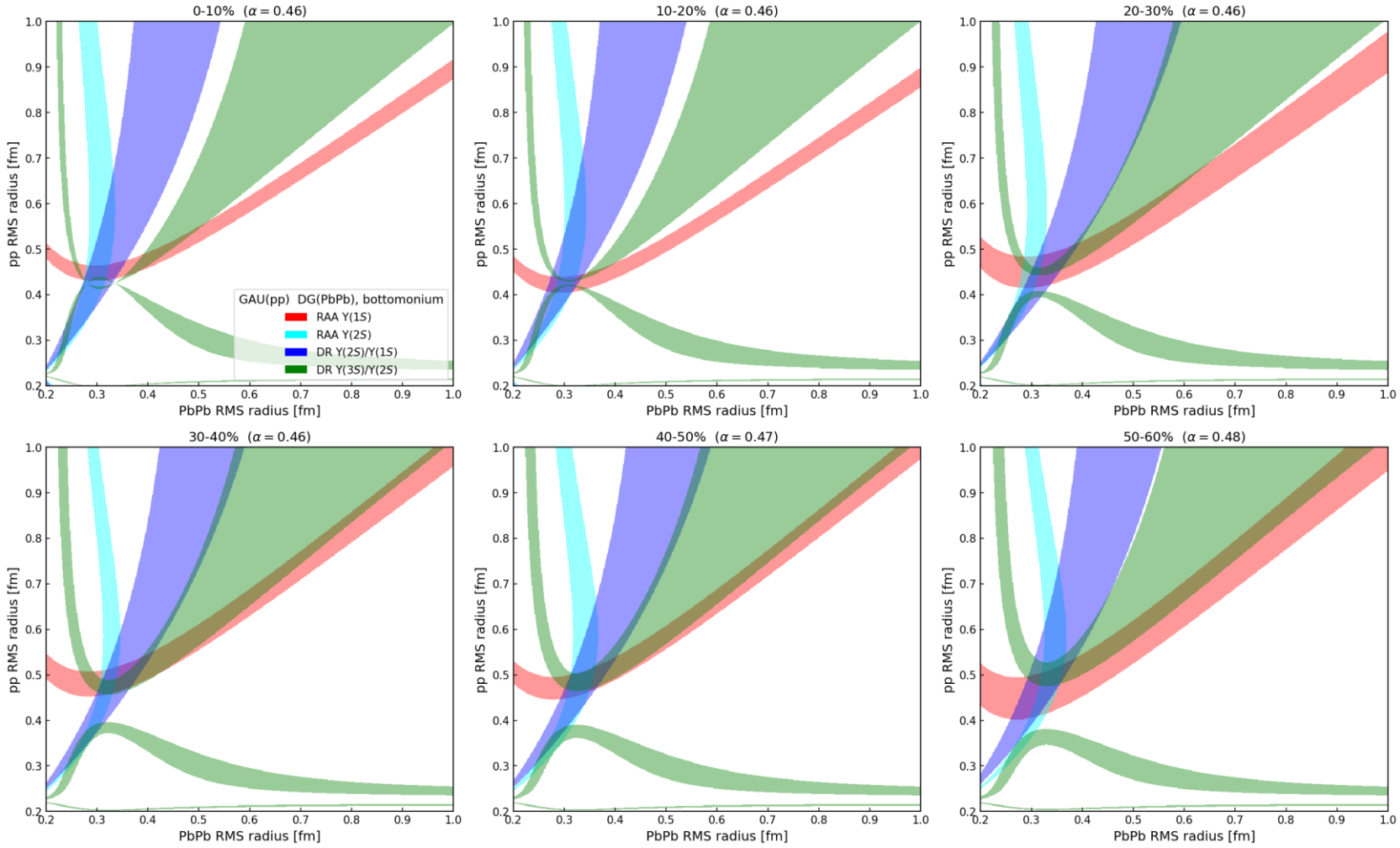






What we find: Hidden-Bottom vs Centrality

$\Psi^{pp}(\sigma_1)_{c\bar{c}} = N\,Gau(\sigma_1; r)$



$\Psi^{PbPb}(\sigma_1, \alpha)_{c\bar{c}} = N[\sqrt{\alpha}\ Gau(\sigma_1; r)\ +\ \sqrt{1-\alpha}\ Gau(R_{HBT}; r)]$

- Lastly, we extended our model to the ϒ mesons. The parameters of the NRQP were fitted to reproduce the bottomonium spectrum to extract the corresponding wf.
- Again, there are **consistent overlaps,** at shorter distances than for charmonium:
  ~0.45 fm in ***pp***
  ~0.3 fm in ***PbPb***
  - ✓ Expected, since the **Debye screening** would force surviving in-medium bottomonium to be **smaller** than the charmonium.
- With varying centrality, the **compact fraction α** is **more constrained** than for charmonia**.**

Conclusions & Further Prospects

We showed:

- A **simple quantum mechanical model** can provide a **good description of the experimental data** on the hadronization of charmonia and bottomonia from the QGP medium.
- Just before hadronization, we find evidence of a **compact, bound-state like** $c\bar{c}$, and of an **extended component** which occupies the whole QGP volume, as determined by the HBT.
- On the other hand, we find evidence that the X(3872) has a **dominant LEU component** together with a **small compact component**.

Further prospects:

- **CMS work in progress** to highlight $X(3872)$ **production dependencies** in run 3 heavy-ion collisions (H. Legoinha, L. Yao, N. Leonardo, Zhen Hu, et al).
- Extend this framework to other exotic states like the T_{cc}^{+}, the **hybrid** $\Upsilon(4260)$ and the **all charm** $X(6900)$.
- Incorporate **open-flavor degrees-of-freedom:** D_s and B_s mesons.

The End

Thank you for your attention!

Work available at: arxiv.org/pdf/2606.23261

Work partly supported by:

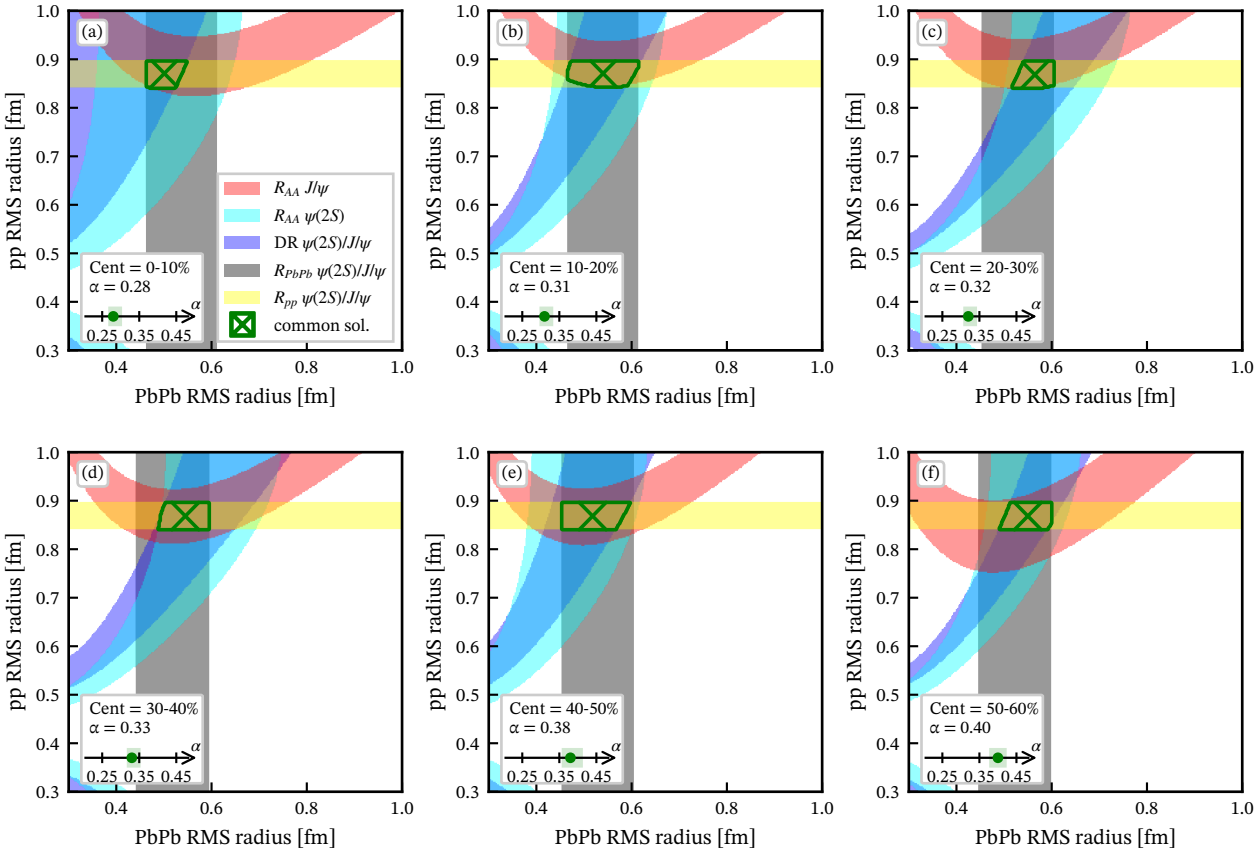
Fundação para a Ciência e a Tecnologia

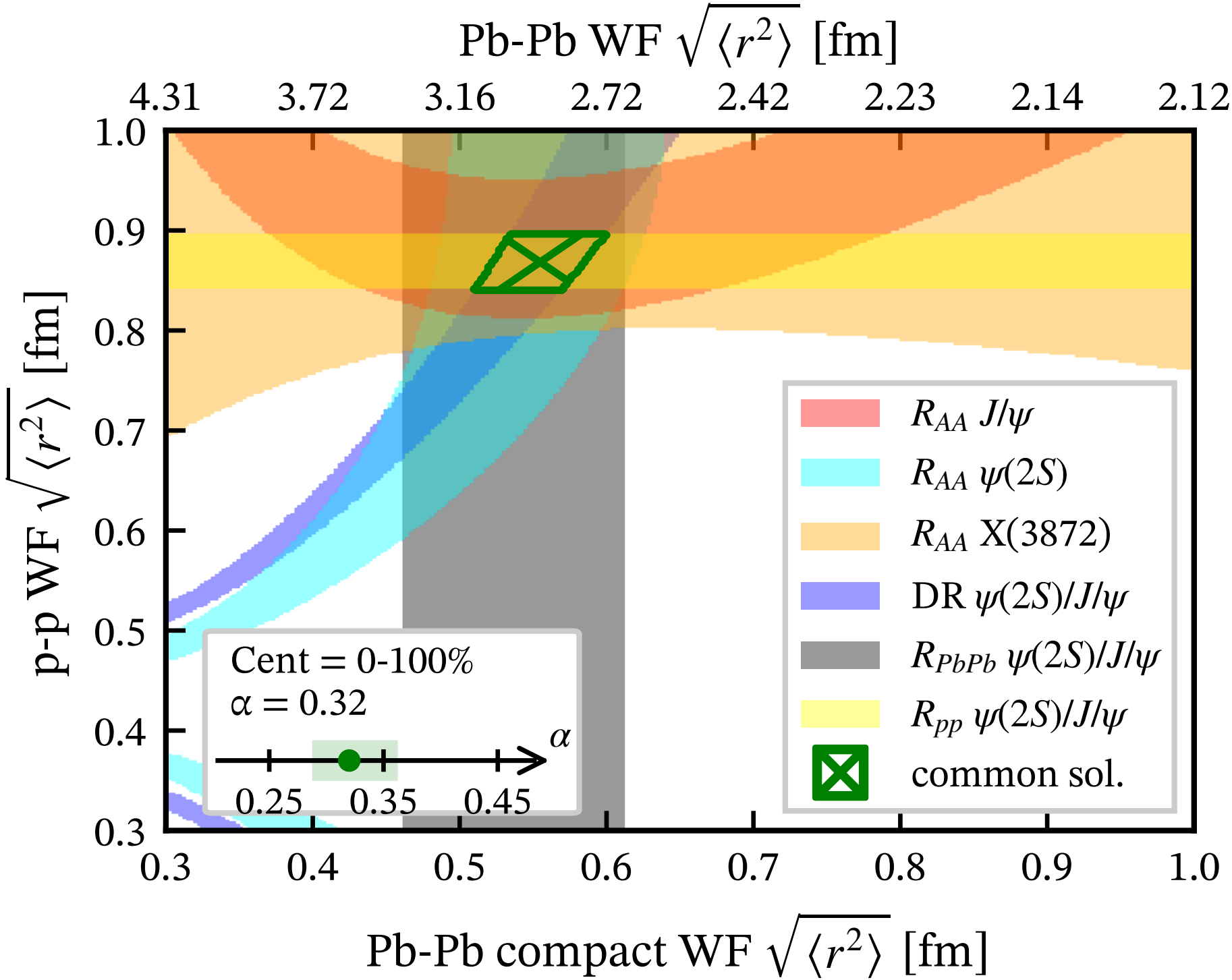
CeFEMA

Project UID/04540, CeFEMA, Centre of Physics, Engineering and Advanced Materials.

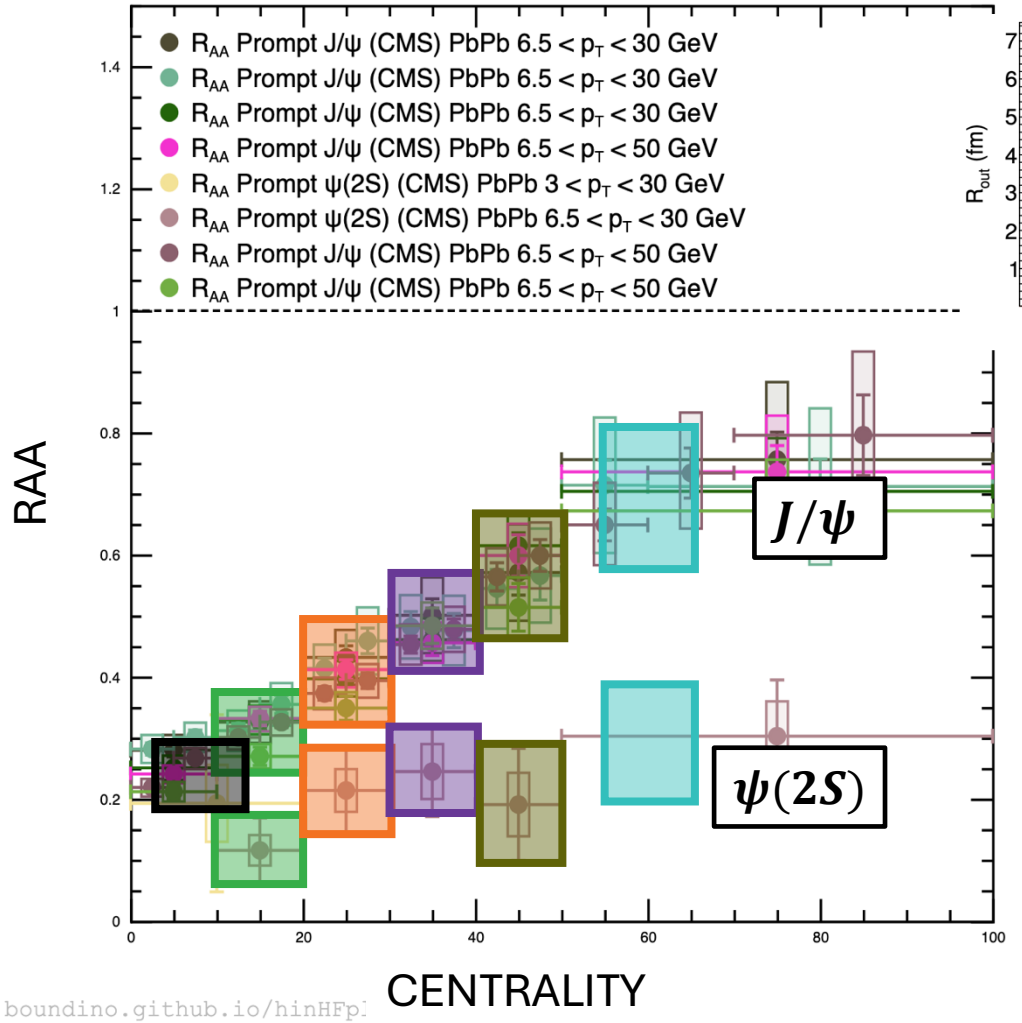
LIP

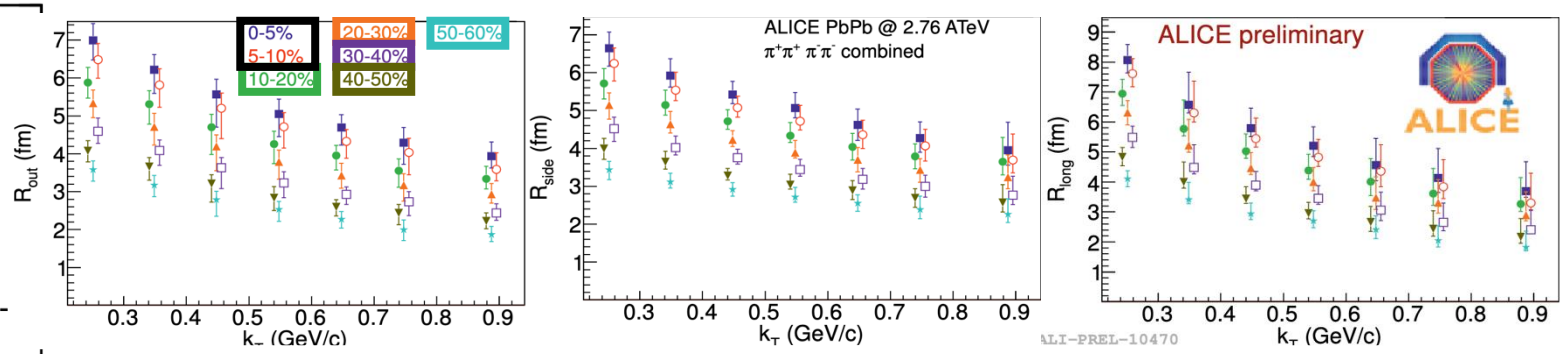
Backup Slides


(a)
(b)
(c)
(d)
(e)
(f)
pp RMS radius [fm]
PbPb RMS radius [fm]
R_{AA} J/ψ
R_{AA} $\psi(2S)$
DR $\psi(2S)/J/\psi$
R_{PbPb} $\psi(2S)/J/\psi$
R_{pp} $\psi(2S)/J/\psi$
common sol.
Cent = 0-10%
α = 0.28
Cent = 10-20%
α = 0.31
Cent = 20-30%
α = 0.32
Cent = 30-40%
α = 0.33
Cent = 40-50%
α = 0.38
Cent = 50-60%
α = 0.40
α
0.25 0.35 0.45


Pb-Pb WF $\sqrt{\langle r^2 \rangle}$ [fm]
4.31
3.72
3.16
2.72
2.42
2.23
2.14
2.12
p-p WF $\sqrt{\langle r^2 \rangle}$ [fm]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Pb-Pb compact WF $\sqrt{\langle r^2 \rangle}$ [fm]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
R_{AA} J/ψ
R_{AA} $\psi(2S)$
R_{AA} X(3872)
DR $\psi(2S)/J/\psi$
R_{PbPb} $\psi(2S)/J/\psi$
R_{pp} $\psi(2S)/J/\psi$
common sol.
Cent = 0-100%
$\alpha = 0.32$
α
0.25
0.35
0.45

Associating R_{AA} & R_{HBT} measurements vs Centrality



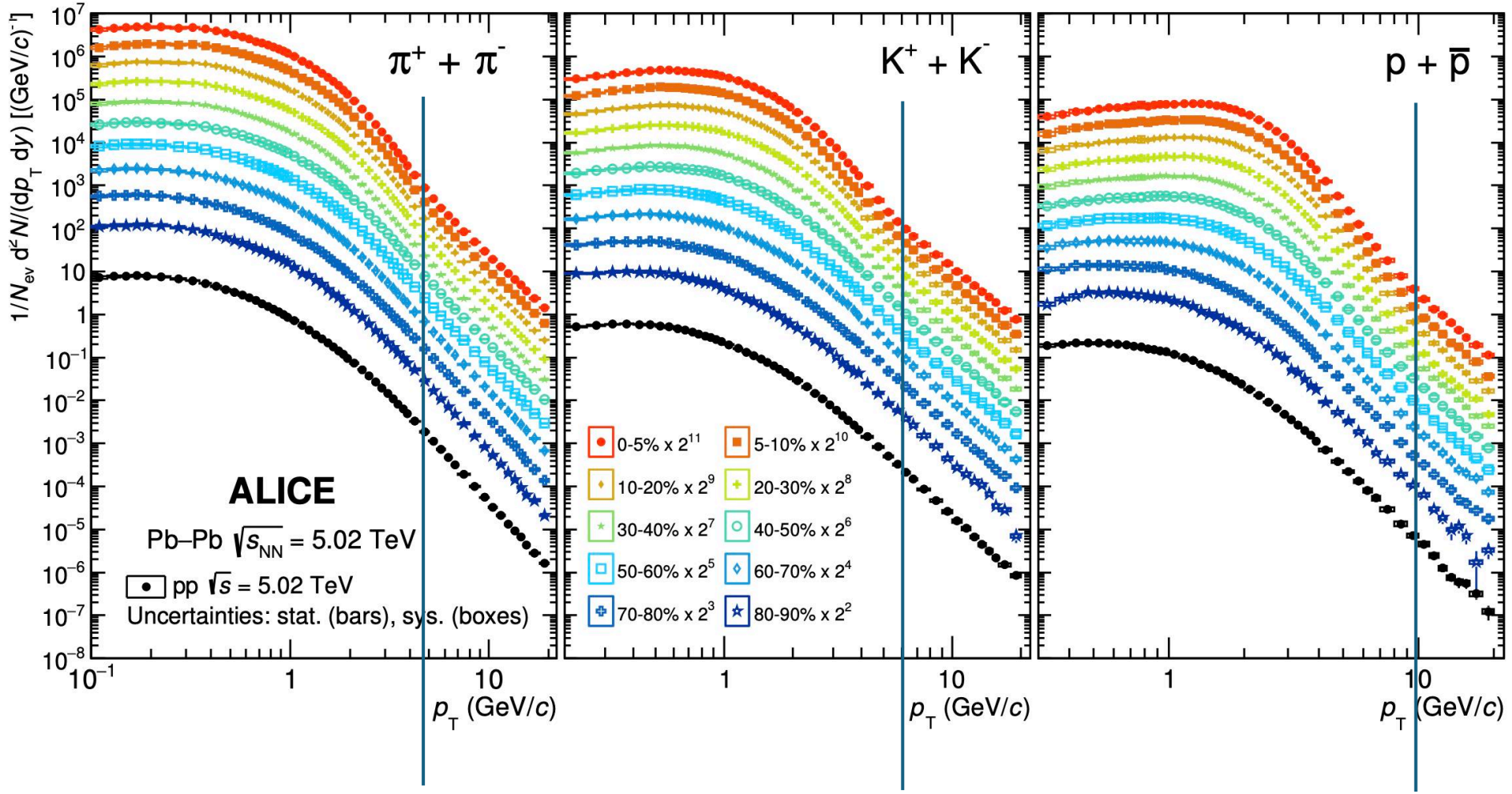


Take $R_{Eff} = \sqrt[3]{R_{out}R_{side}R_{long}}$ at the representative $K_T \in [0.3; 0.4]$ bin

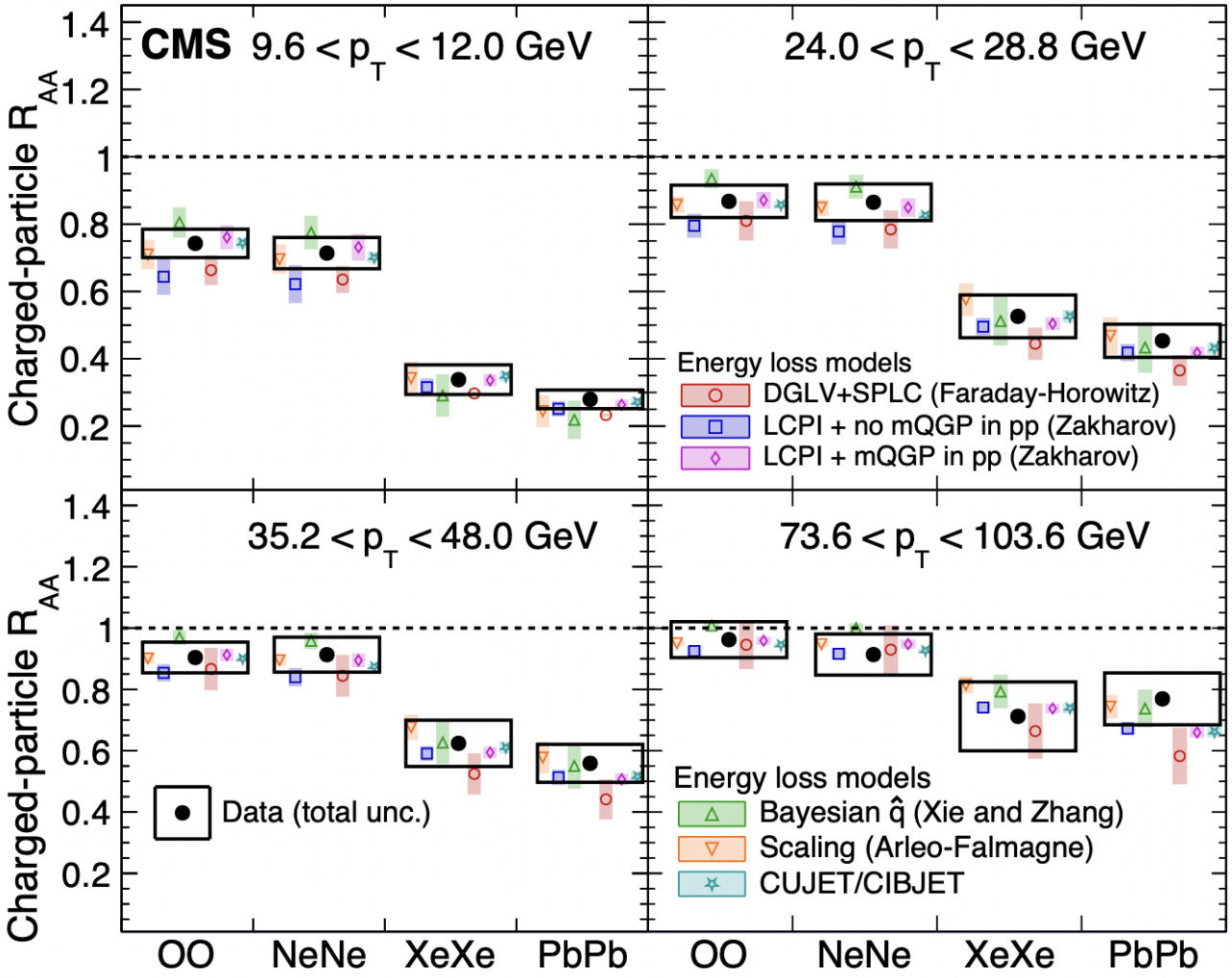
So, for the probed **centrality bins:**

- $0 - 10\%$: $R_{Eff} \sim 6.0fm$ $R_{AA}^{J/\Psi} \in [0.20; 0.31]$ $R_{AA}^{\Psi(2S)} \in [0.05; 0.34]$
- $10 - 20\%$: $R_{Eff} \sim 5.4fm$ $R_{AA}^{J/\Psi} \in [0.25; 0.38]$ $R_{AA}^{\Psi(2S)} \in [0.06; 0.17]$
- $20 - 30\%$: $R_{Eff} \sim 4.7fm$ $R_{AA}^{J/\Psi} \in [0.33; 0.50]$ $R_{AA}^{\Psi(2S)} \in [0.15; 0.28]$
- $30 - 40\%$: $R_{Eff} \sim 4.1fm$ $R_{AA}^{J/\psi} \in [0.41; 0.57]$ $R_{AA}^{\Psi(2S)} \in [0.18; 0.33]$
- $40 - 50\%$: $R_{Eff} \sim 3.7fm$ $R_{AA}^{J/\Psi} \in [0.46; 0.67]$ $R_{AA}^{\Psi(2S)} \in [0.10; 0.30]$
- $50 - 60\%$: $R_{Eff} \sim 3.2fm$ $R_{AA}^{J/\Psi} \in [0.58; 0.82]$ $R_{AA}^{\Psi(2S)} \in [0.20; 0.40]$

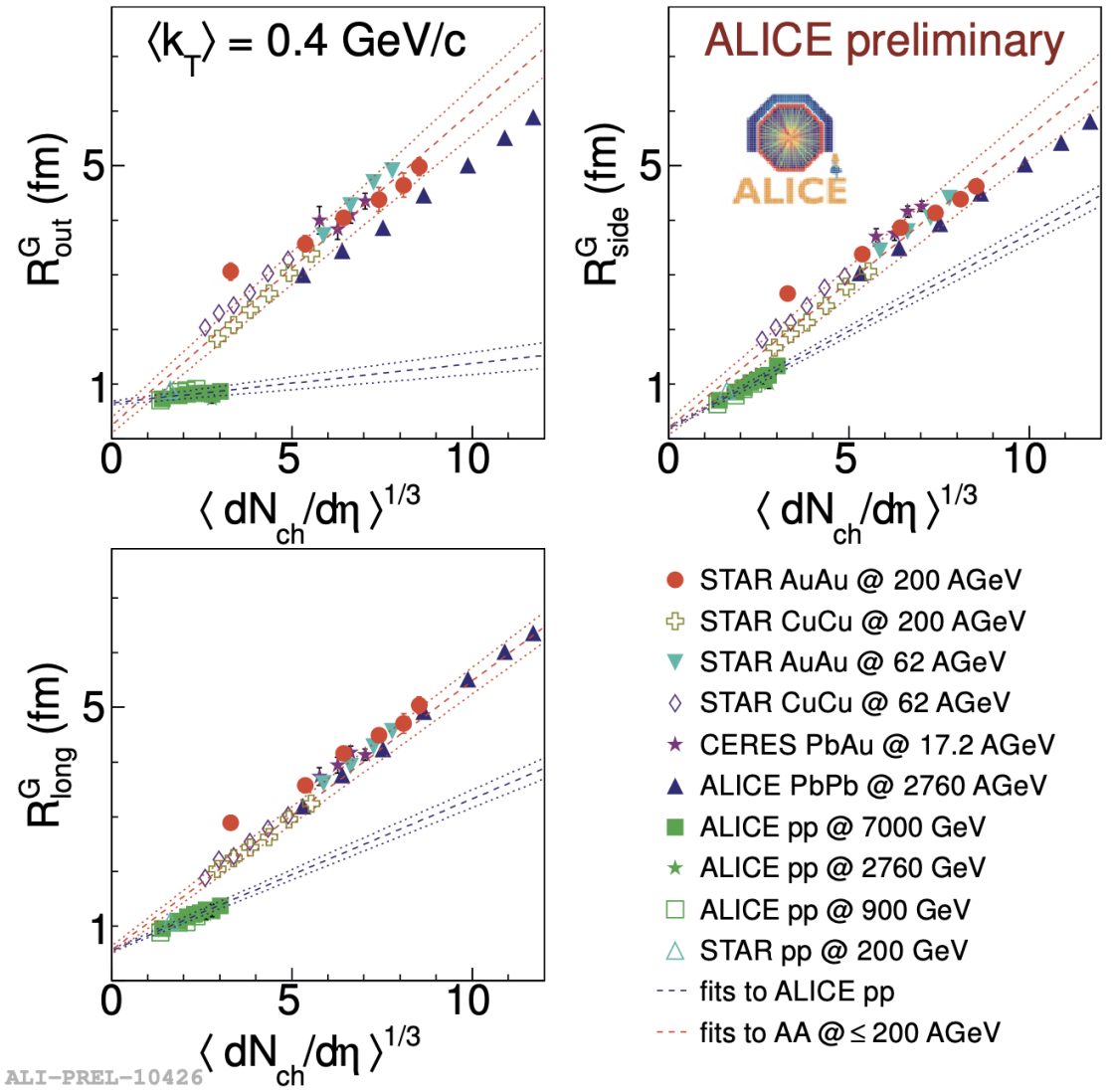
Matching at the Inflexion Point



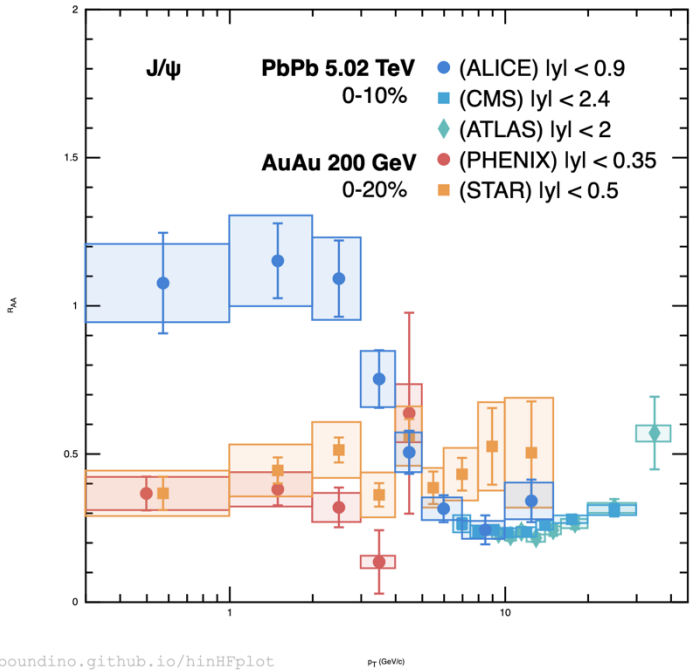
“Mini-QGP” in pp (CMS)



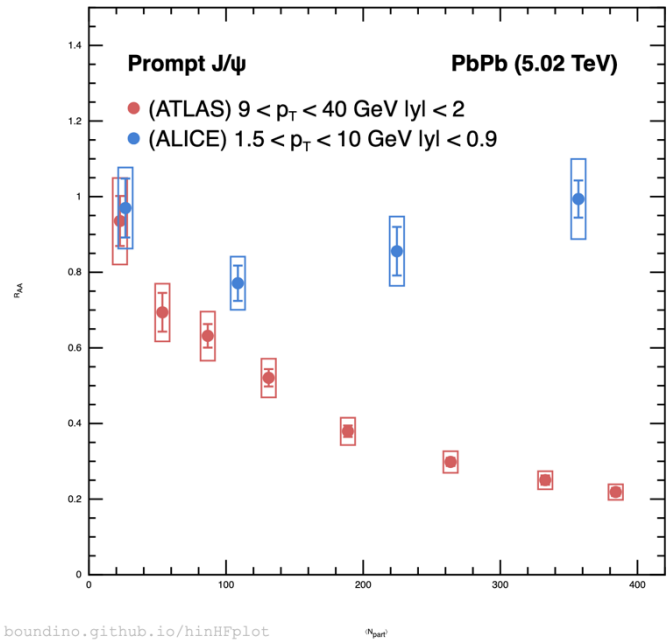
"Mini-QGP" in pp (ALICE)



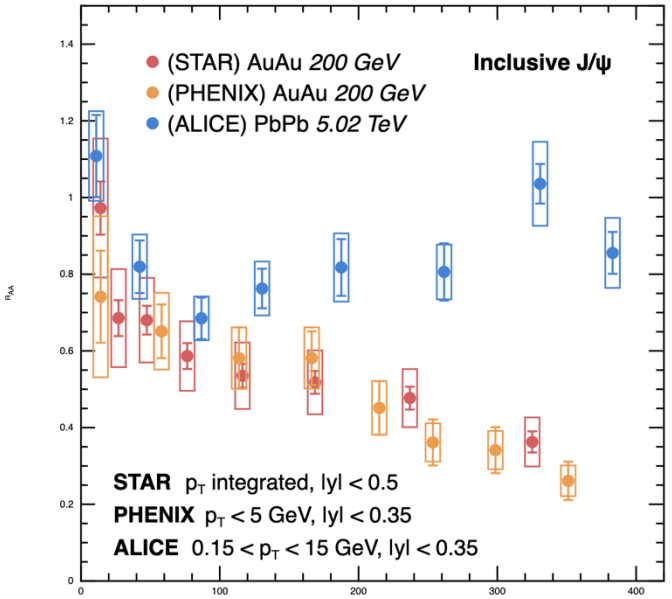
Charm recombination at LHC



→ EPJC 78 (2018) 762 → EPJC 78 (2018) 509
→ PRL 98 (2007) 232301 → PLB 797 (2019) 134917
→ PLB 849 (2024) 138451



→ EPJC 78 (2018) 762 → JHEP 02 (2024) 066

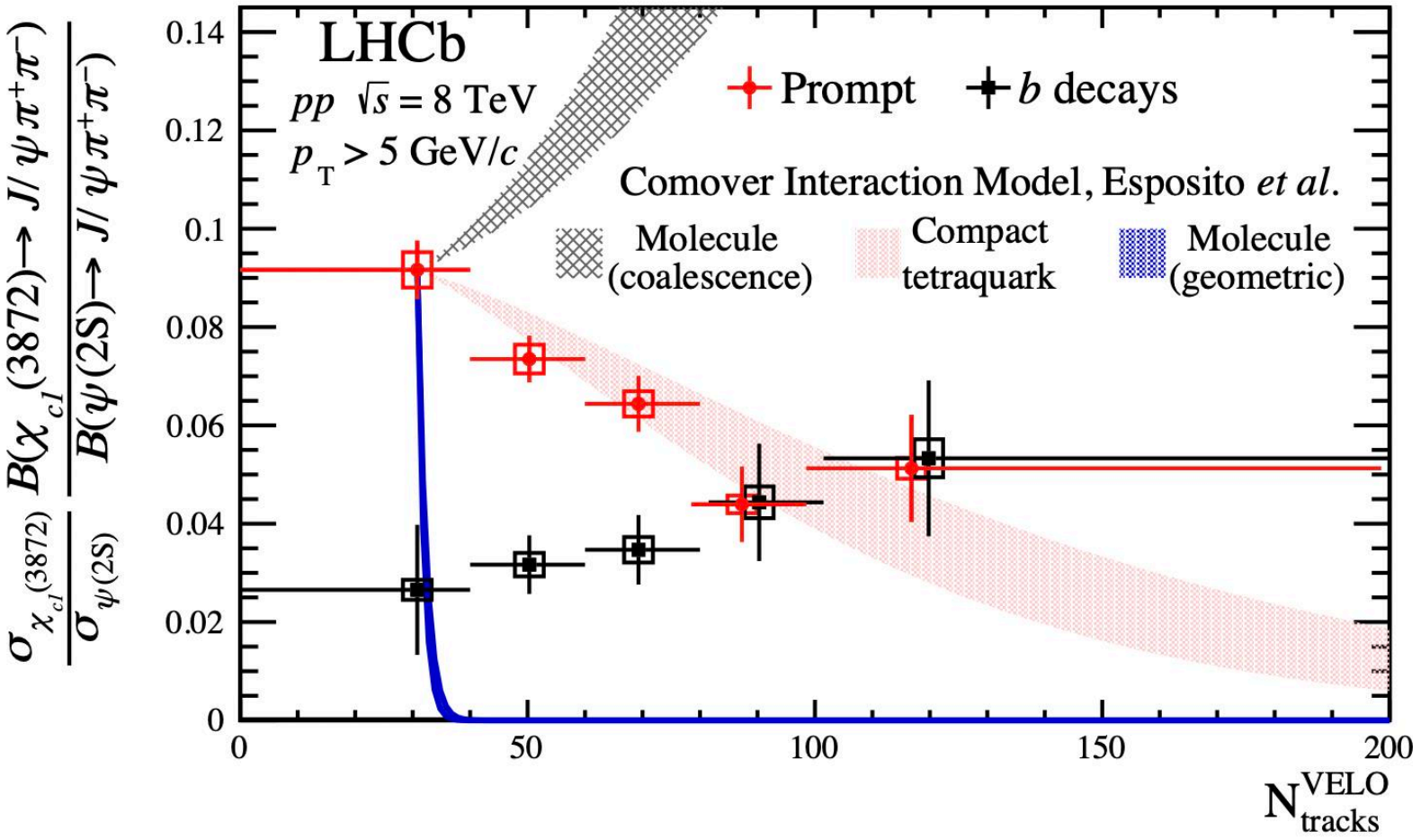


At the LHC charm cross section is much larger than at RHIC.

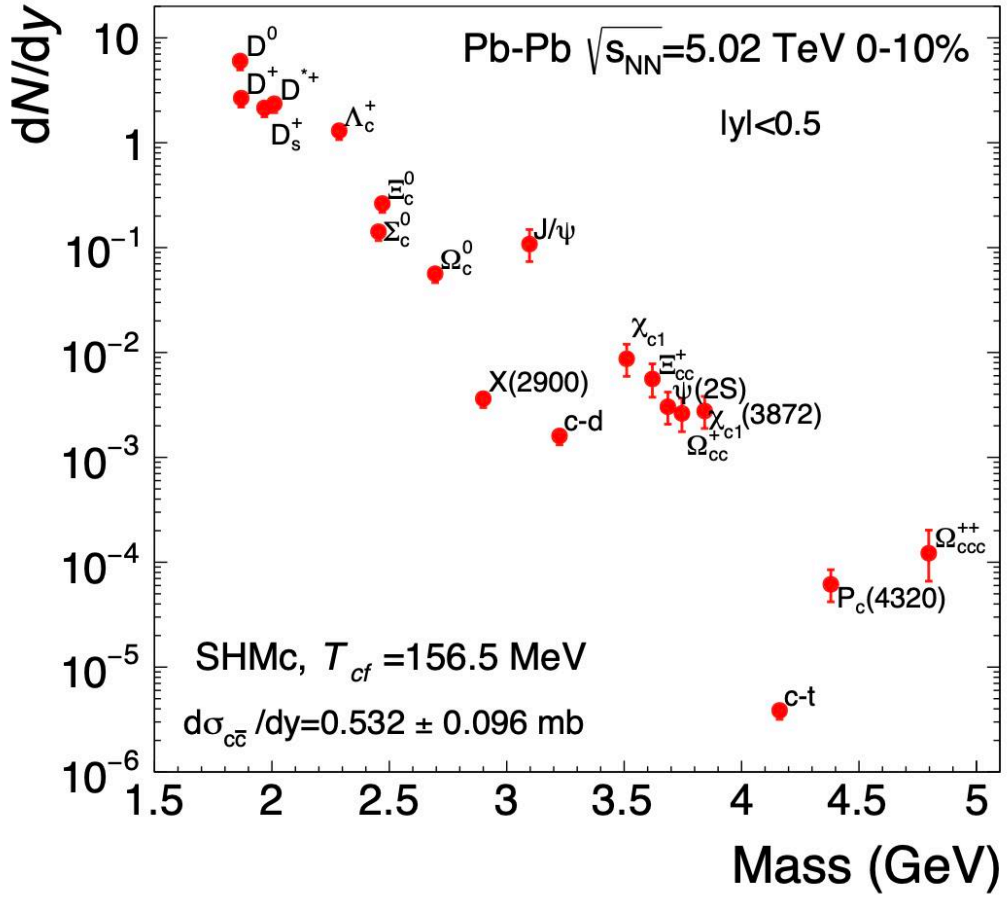
At low pT recombination of charm quarks can happen

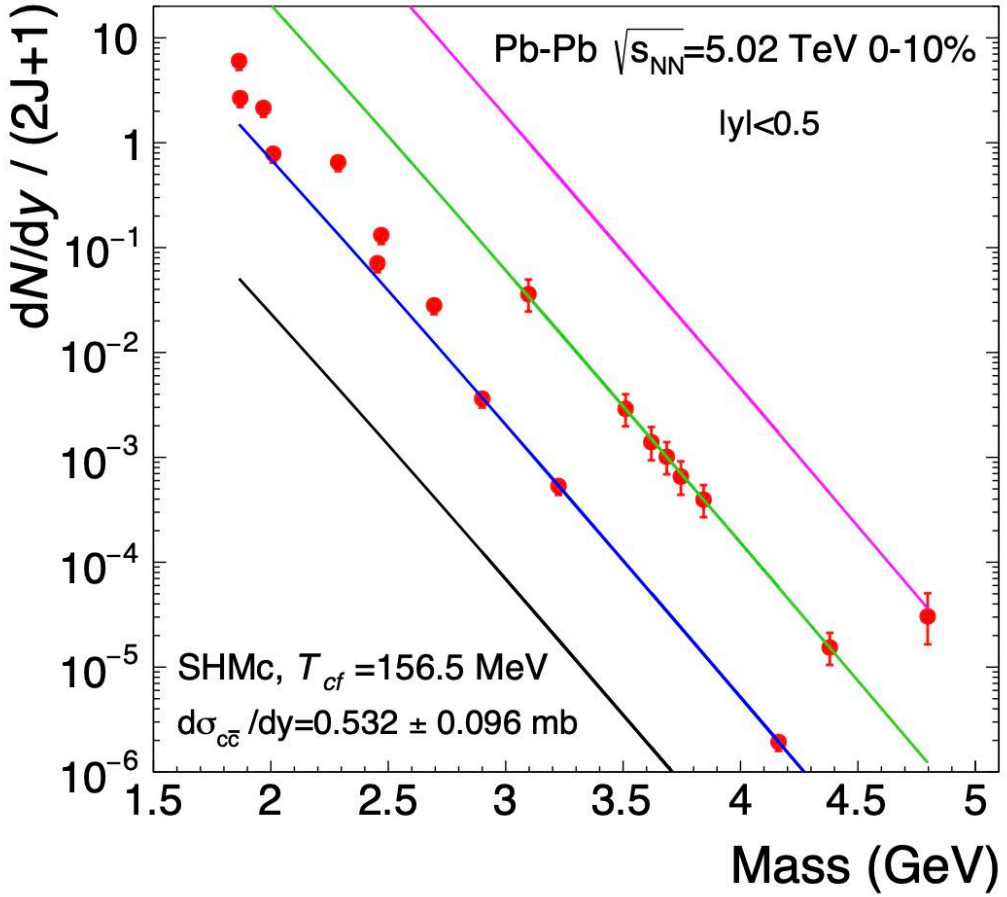
Difference is clear when compared to RHIC

Tetraquark State



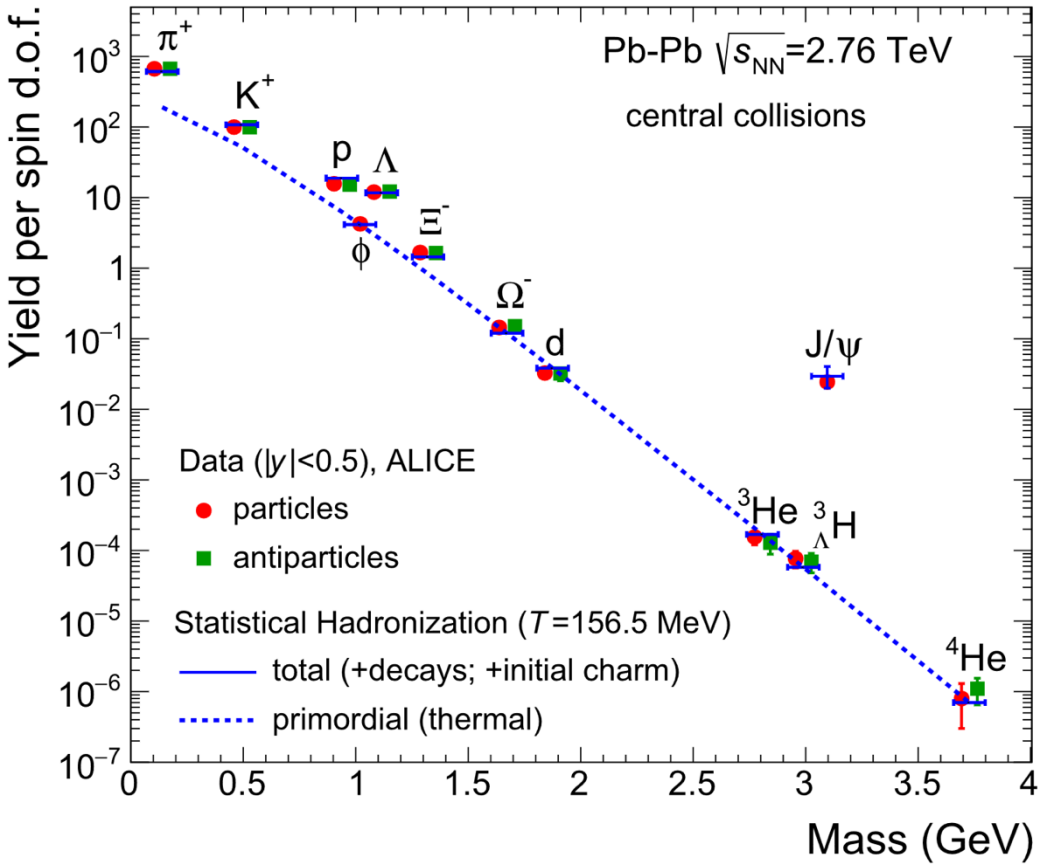
Multiple-charm Hierarchy in the SHM



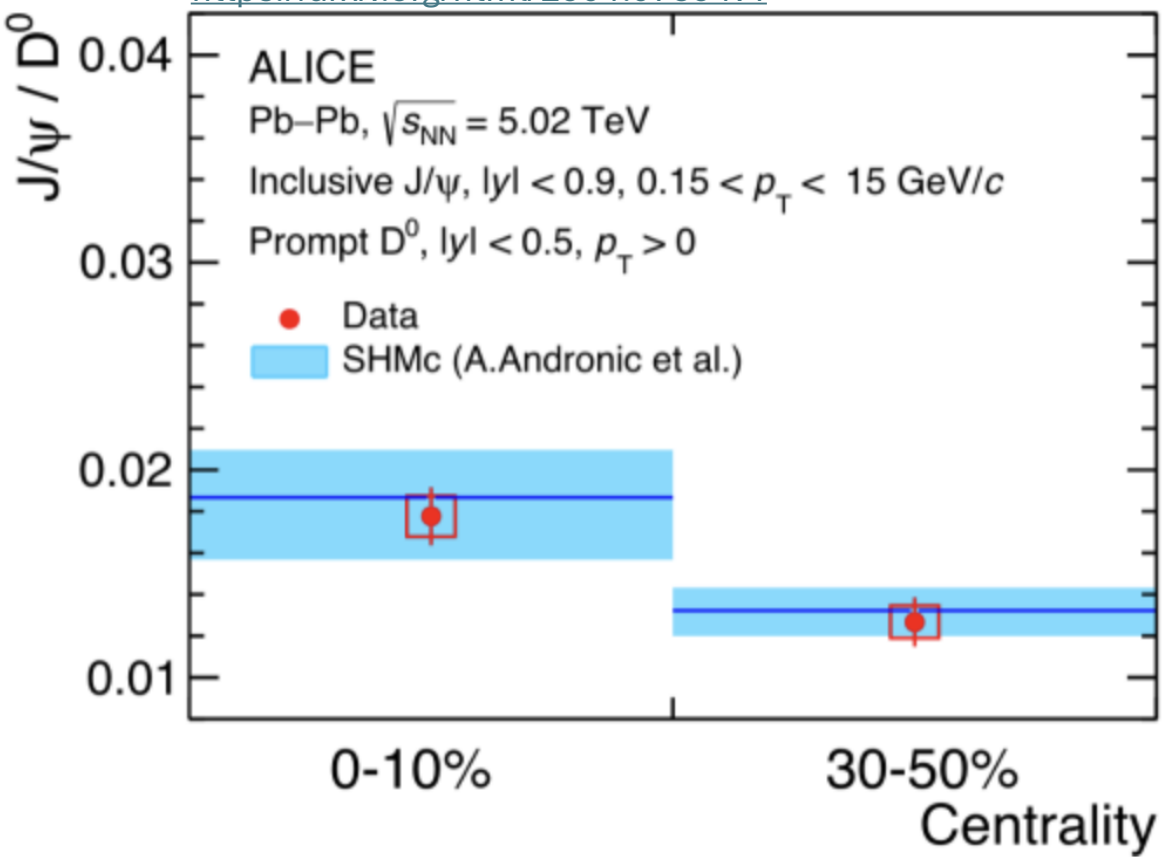


A. Andronic et al.

SHM & SHMc

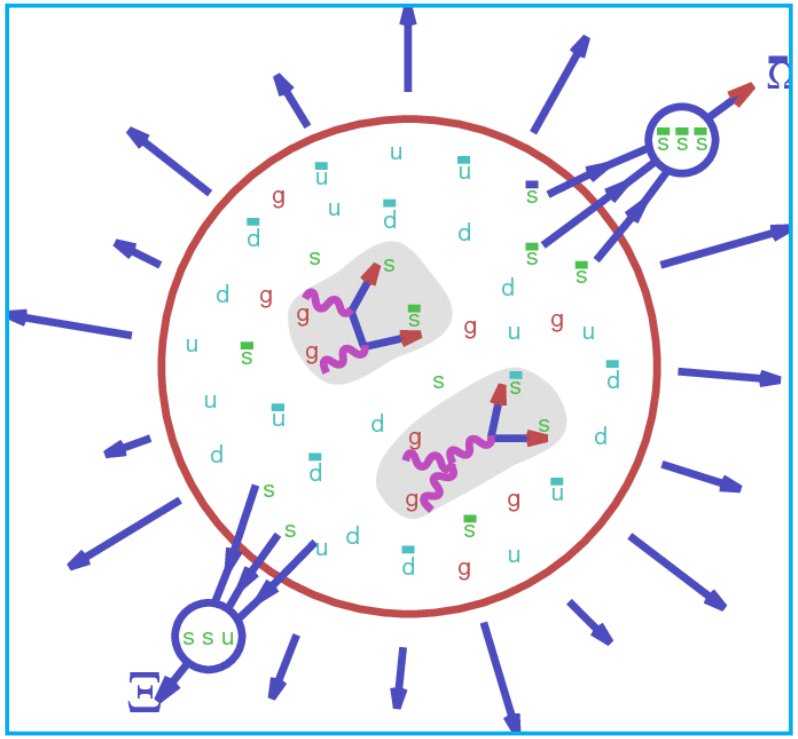


https://arxiv.org/html/2604.07564v1



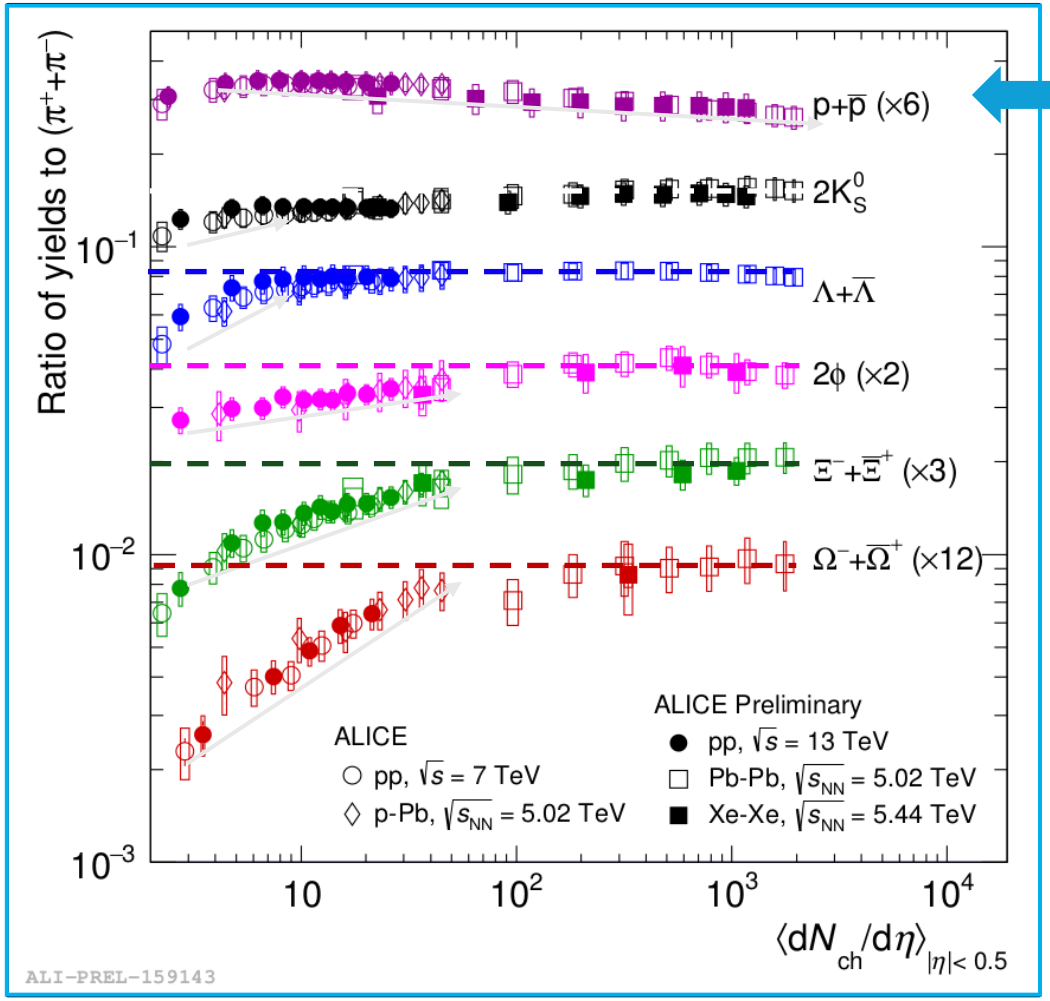
$$\left.\frac{d\rho_a}{dp_T}\right|_{p_T^{eff}} = \frac{g_a}{8\pi^2}\, p_T^{eff} \int_{-1.6}^{1.6} dy\; e^{(-m_T^a \cosh y)/T}$$

Soft Probes: Strangeness Enhancement



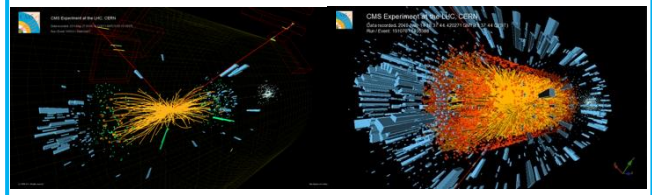
Thermodynamics + QCD:
Strangeness production follows from in-medium gluon fusion at $T_{QGP} > T_{m_s}$

$$gg \rightarrow s\bar{s}, d\bar{d}, u\bar{u}$$



ALICE measured **open and closed strange hadron yields** as function of event **Multiplicity**

Multiplicity, number of (charged) **tracks,** is a proxy for the **size** of the **QGP** system



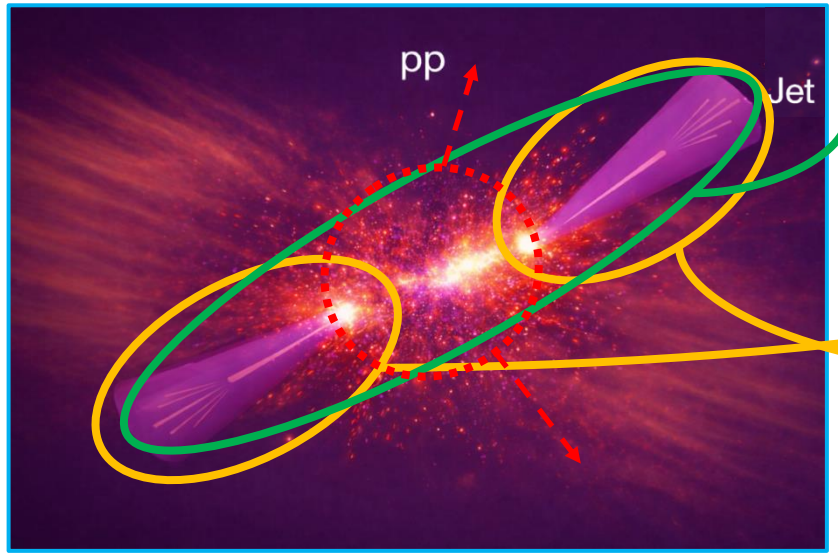
Small Mult (**pp**) **vs** High Mult (**PbPb**)

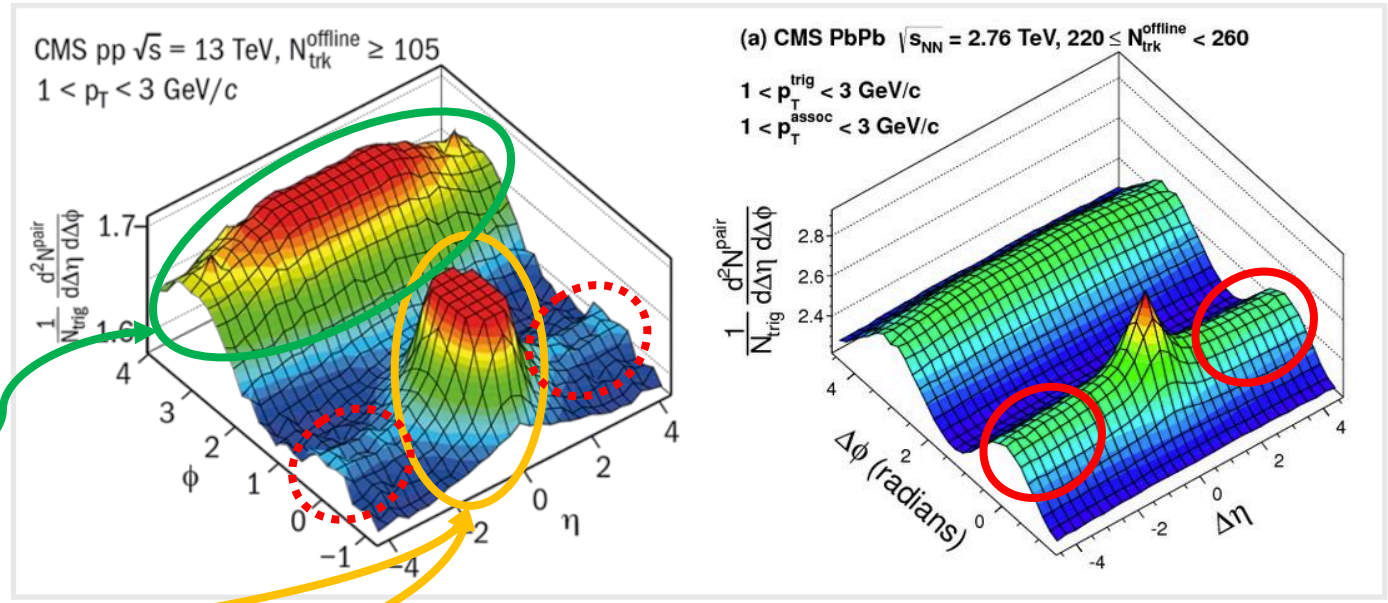
Strange to non-strange particles **ratio** at **high-Mult** (PbPb collisions) is stable:
→ Hit of in-medium thermal strangeness production growing with system size

Soft Probes: **Collective Flow**

High energy **quarks** and **gluons** evolve into a **collimated beam** of hadrons, a **jet**.

Jets from **hard scatterings** must be **symmetrically** produced in **pairs!**



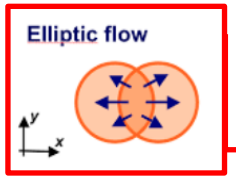


CMS measured **2-particle correlation** in **pp** (left) and **PbPb** (right)

$\Delta\eta \sim \Delta\phi \sim 0$ – particles from **same jet**

$\Delta\phi \sim \pi$ – particles from **back-to-back jets**

$\Delta\phi \sim 0$ – particles from **QGP medium** → **but ridge also in pp ?!**



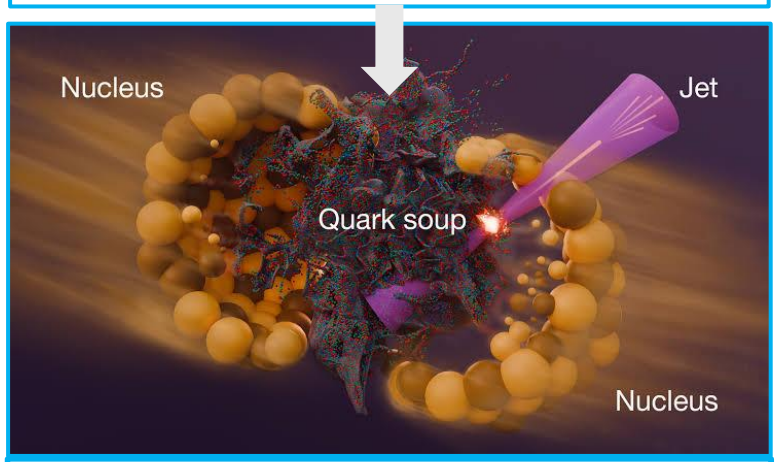
Collective flow (of medium constituents) explains near ridge!

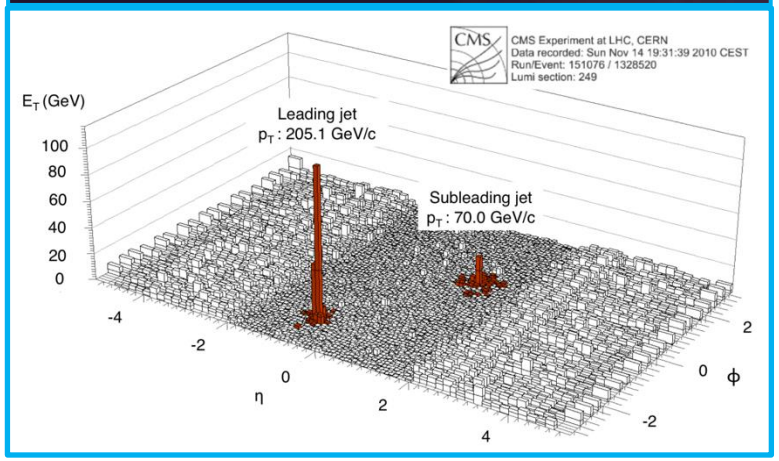
$$C(\Delta\phi) \propto 1 + 2v_2^2\cos(2\Delta\phi) + 2v_3^2\cos(3\Delta\phi) + \ldots$$

→ No dependence on η → long range correlations

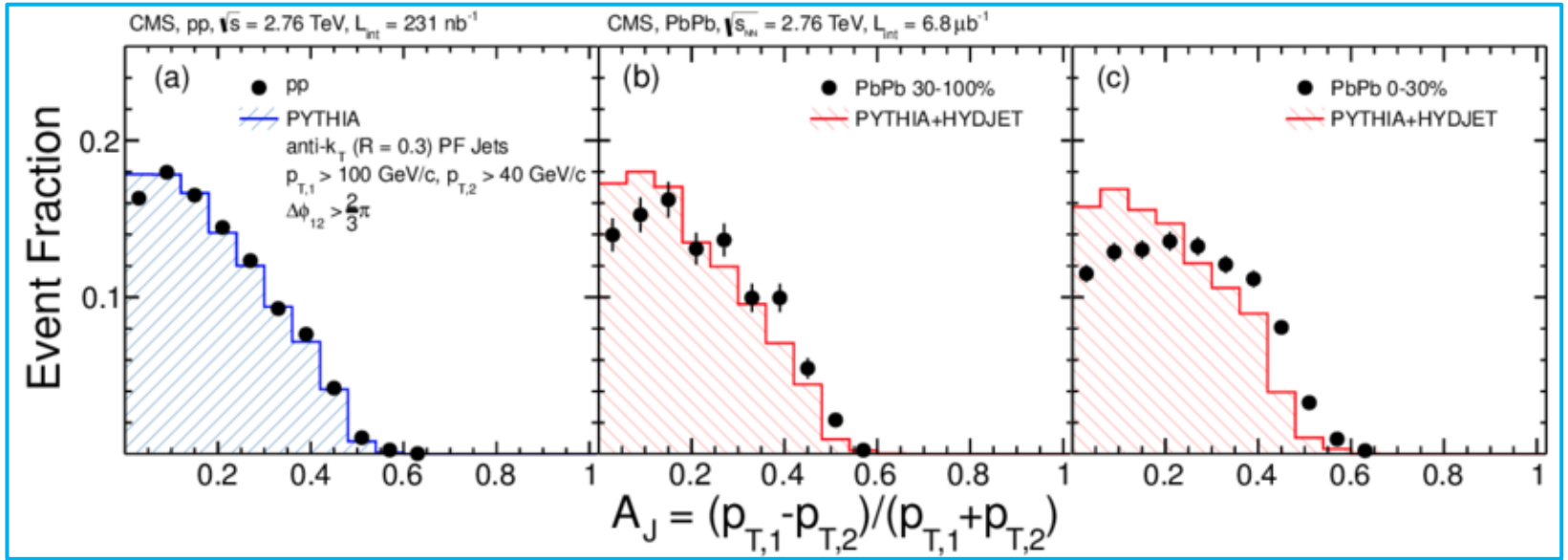
Hard Probes: Jet Quenching

Jets **interact strongly** with **QGP**, **losing energy** and **smearing**





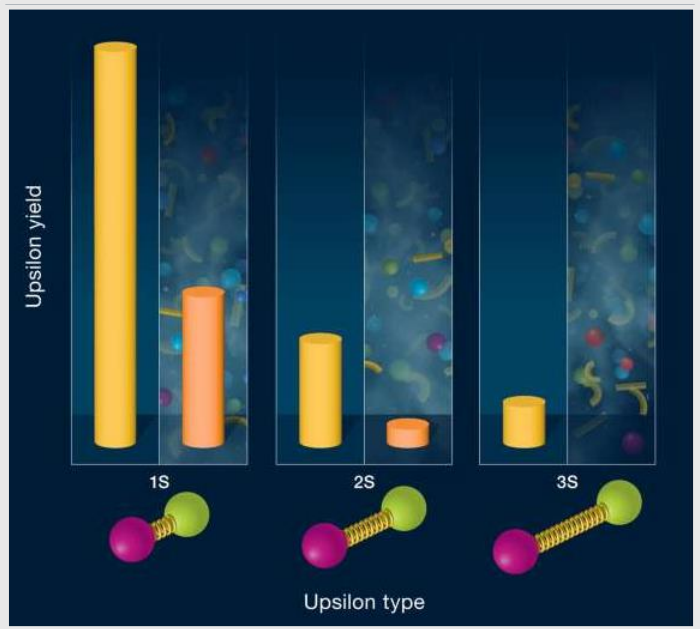
Jet quenching provides direct **evidence** that the **QGP system** created in **heavy-ion collisions** is **dense** and **strongly interacting**.



CMS measured **di-jet asymmetry in pp (a)** and **PbPb (b,c)**

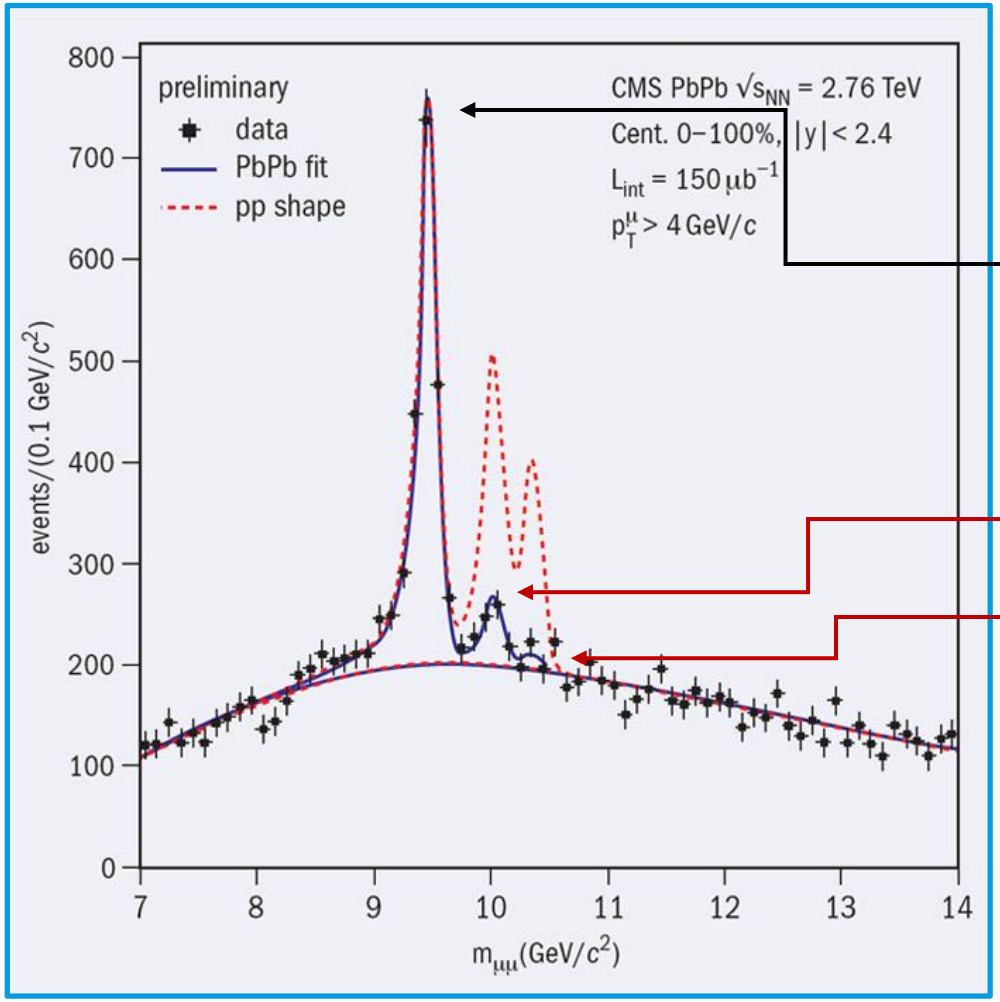
In pp: Low asymmetry expected and **found** (due to ISR / jet fragmentation)
In PbPb: High(er) asymmetry is **expected** and **sequentially found increasing** in **centrality** due to QGP presence. Map back to pp when in peripherical coll.

Hard Probes: **Quarkonia**

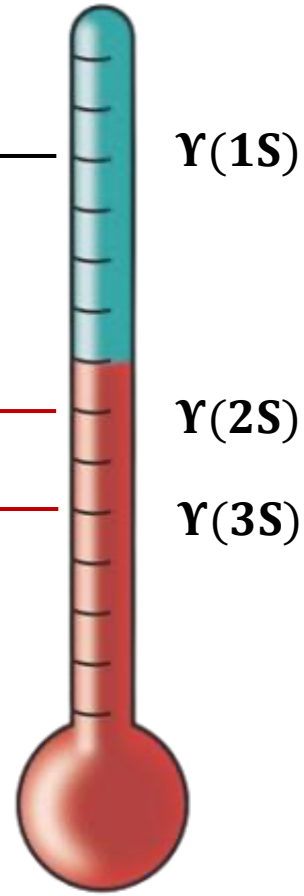


Small binding energy means a **more "fragile"** hadron

Hadron **melting** stand as a probe of **QGP temperature**



Sequential suppression!



Map of concepts and goal

