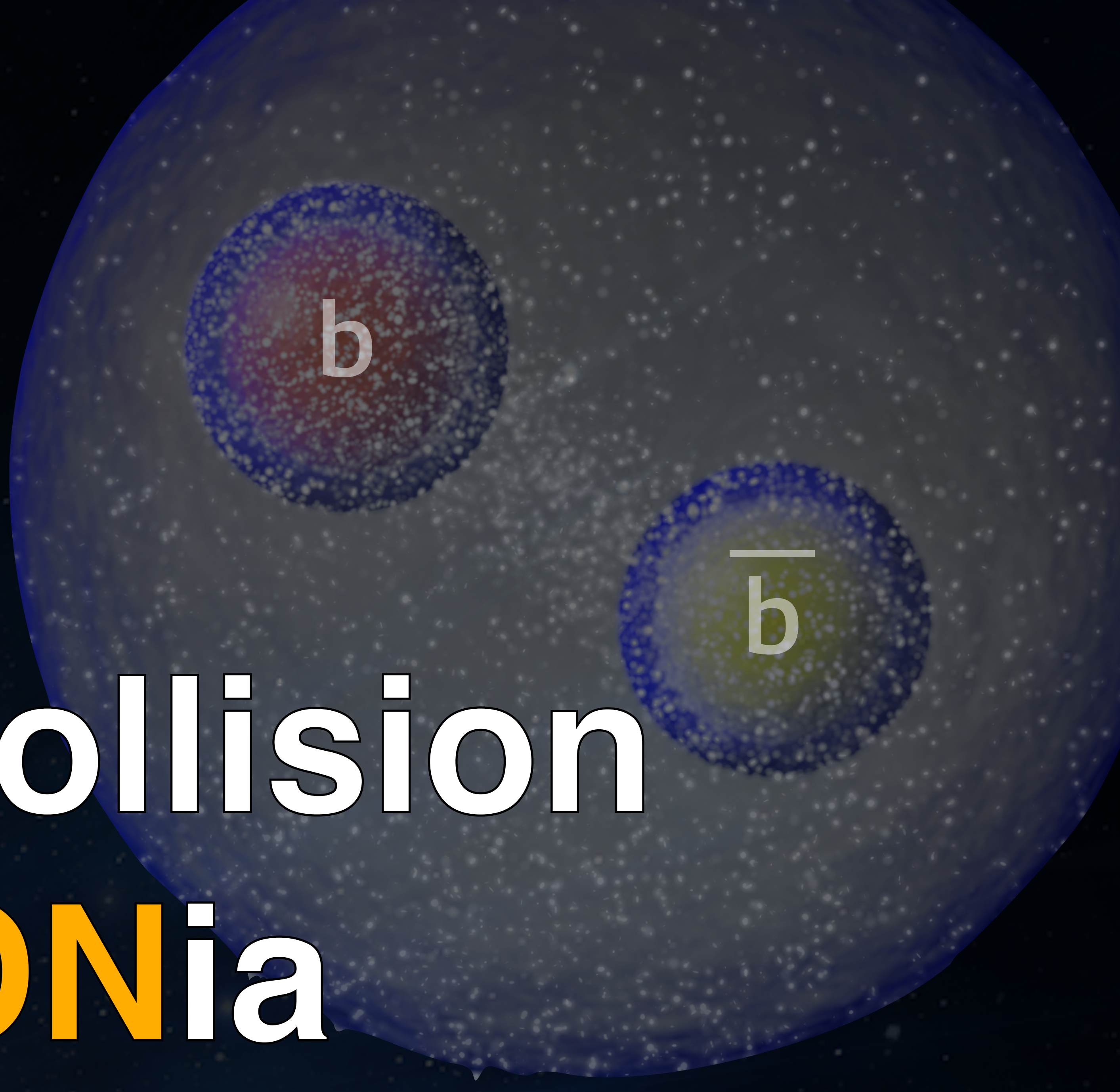
CENuM 2022 CENuM Workshop



Simulation for Heavy IoN Collision with Heavy-quark and ONia

(SHINCHON)

Jinjoo Seo
Inha University

Sanghoon Lim, Jeabeom Park, Junlee Kim
Byungsik Hong, Eun-Joo Kim, MinJung Kweon, Yongsun Kim
Su Houng Lee, Sungtae Cho ,Juhee Hong

2022. 09. 03.

2022 CENuM Workshop

+ small collisions system!

Simulation for Heavy IoN Collision with Heavy-quark and ONia
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Heavy Quarkonia in heavy-ion collisions

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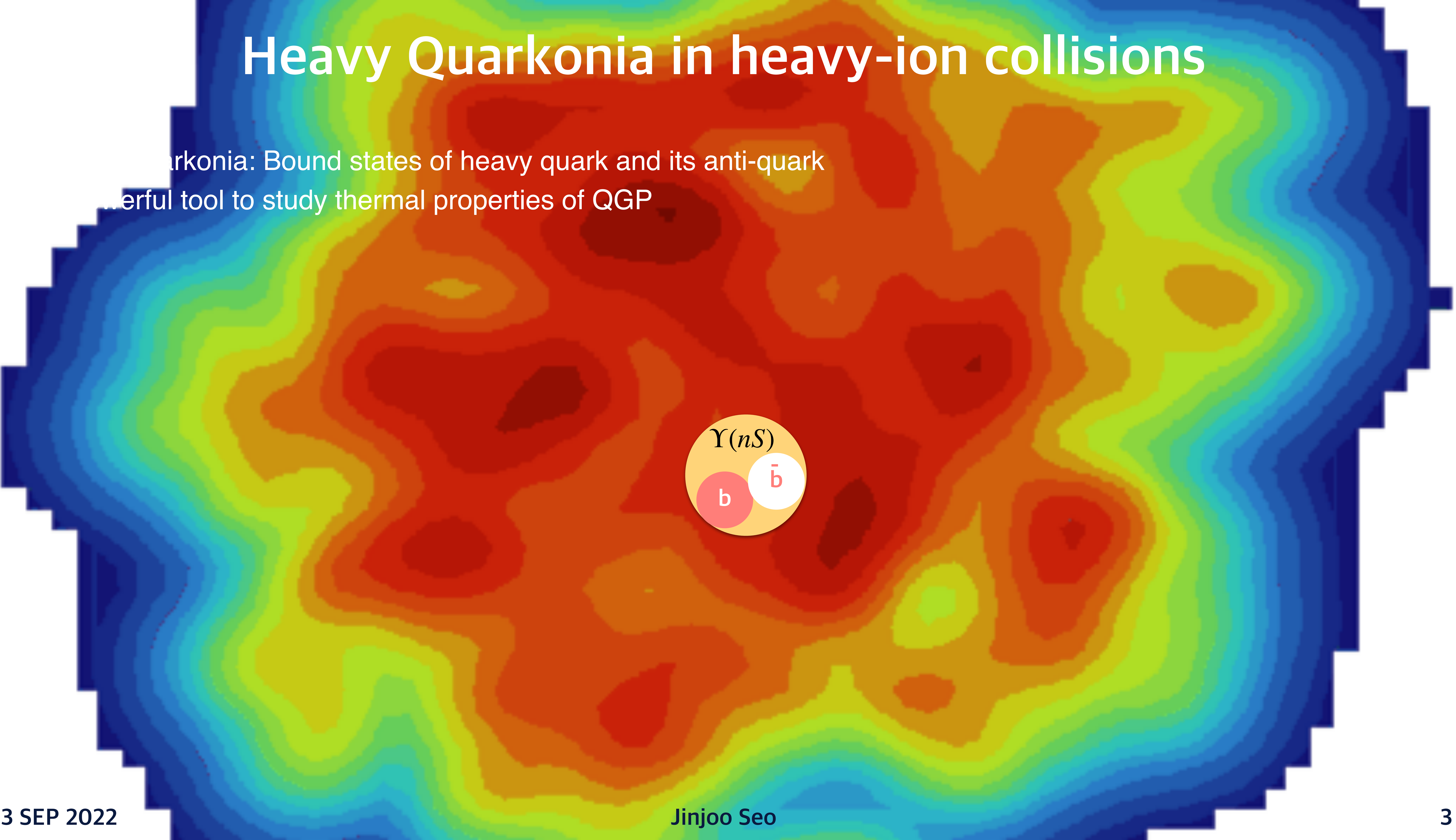

Heavy Quarkonia in heavy-ion collisions

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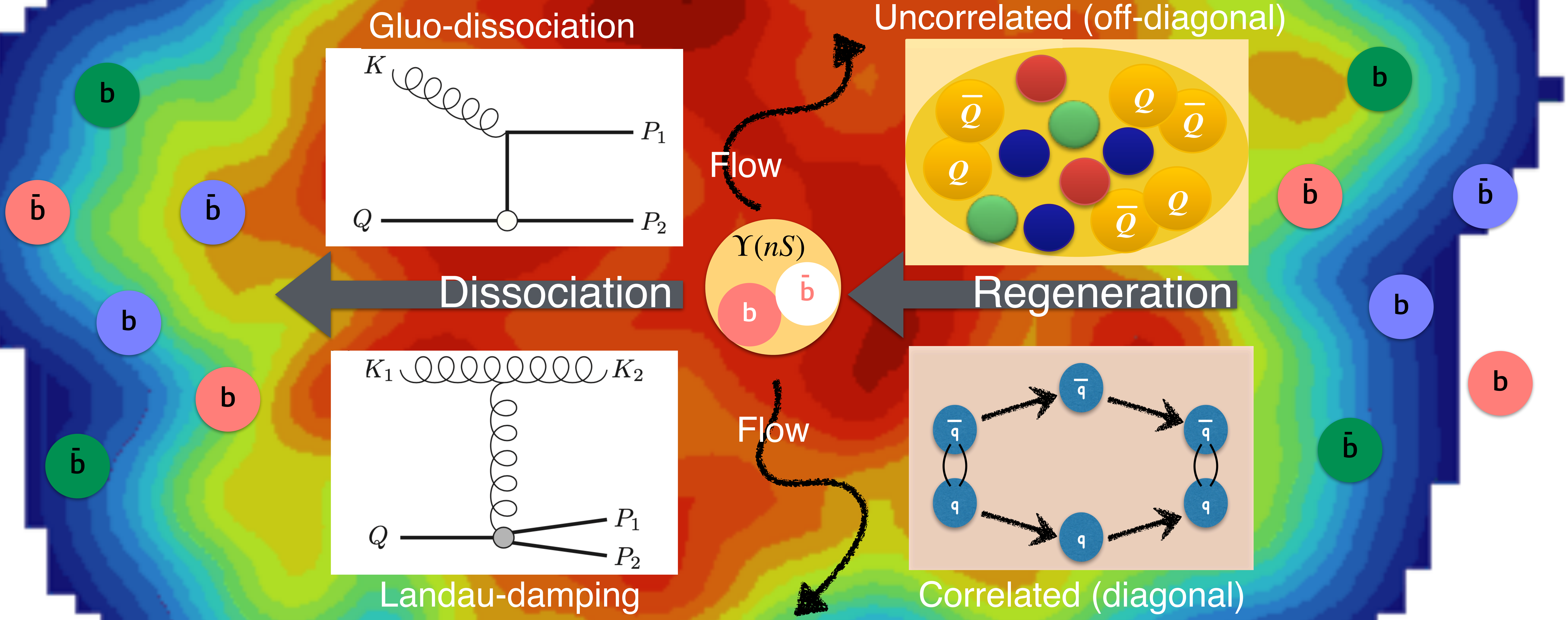
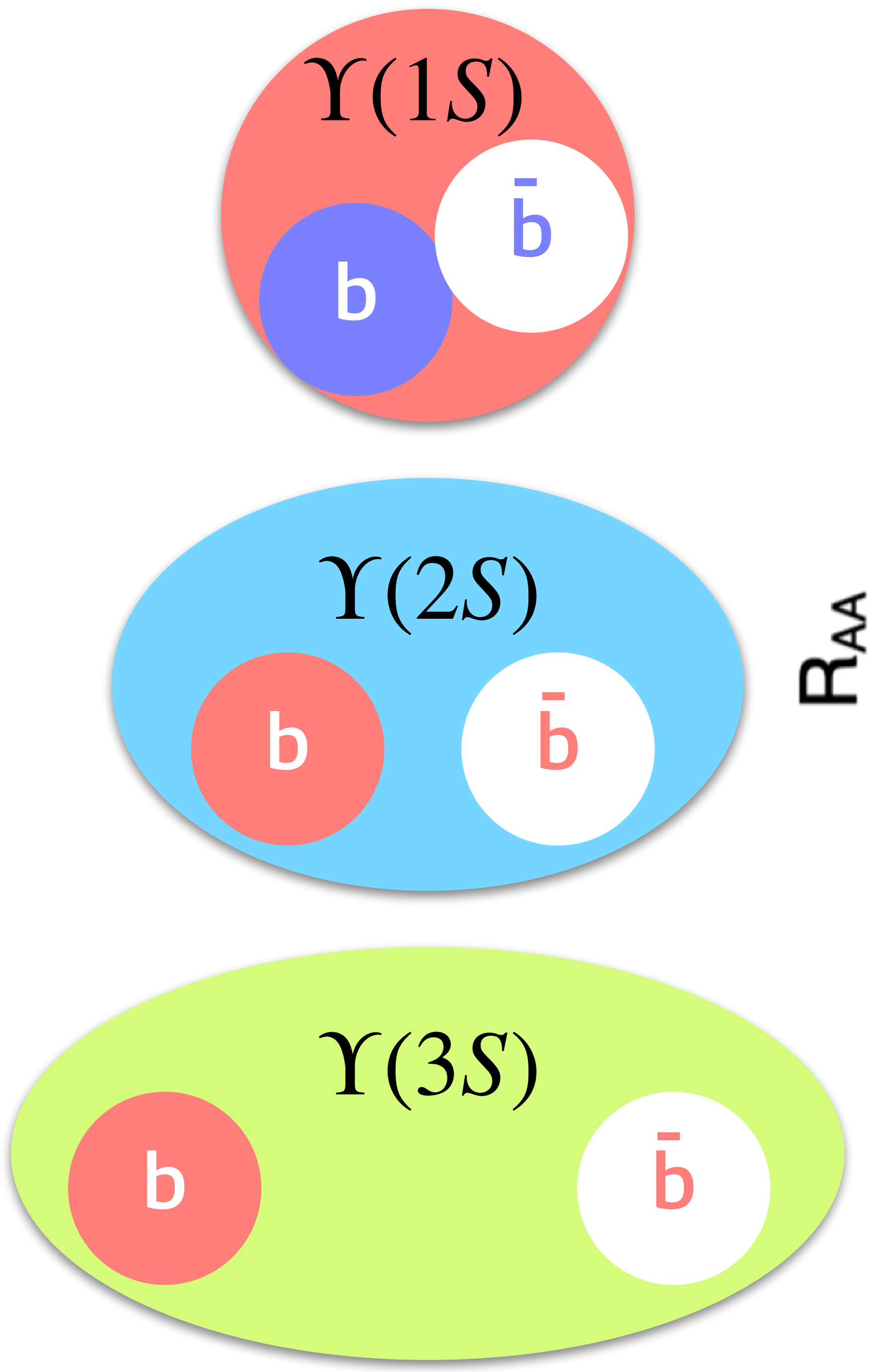
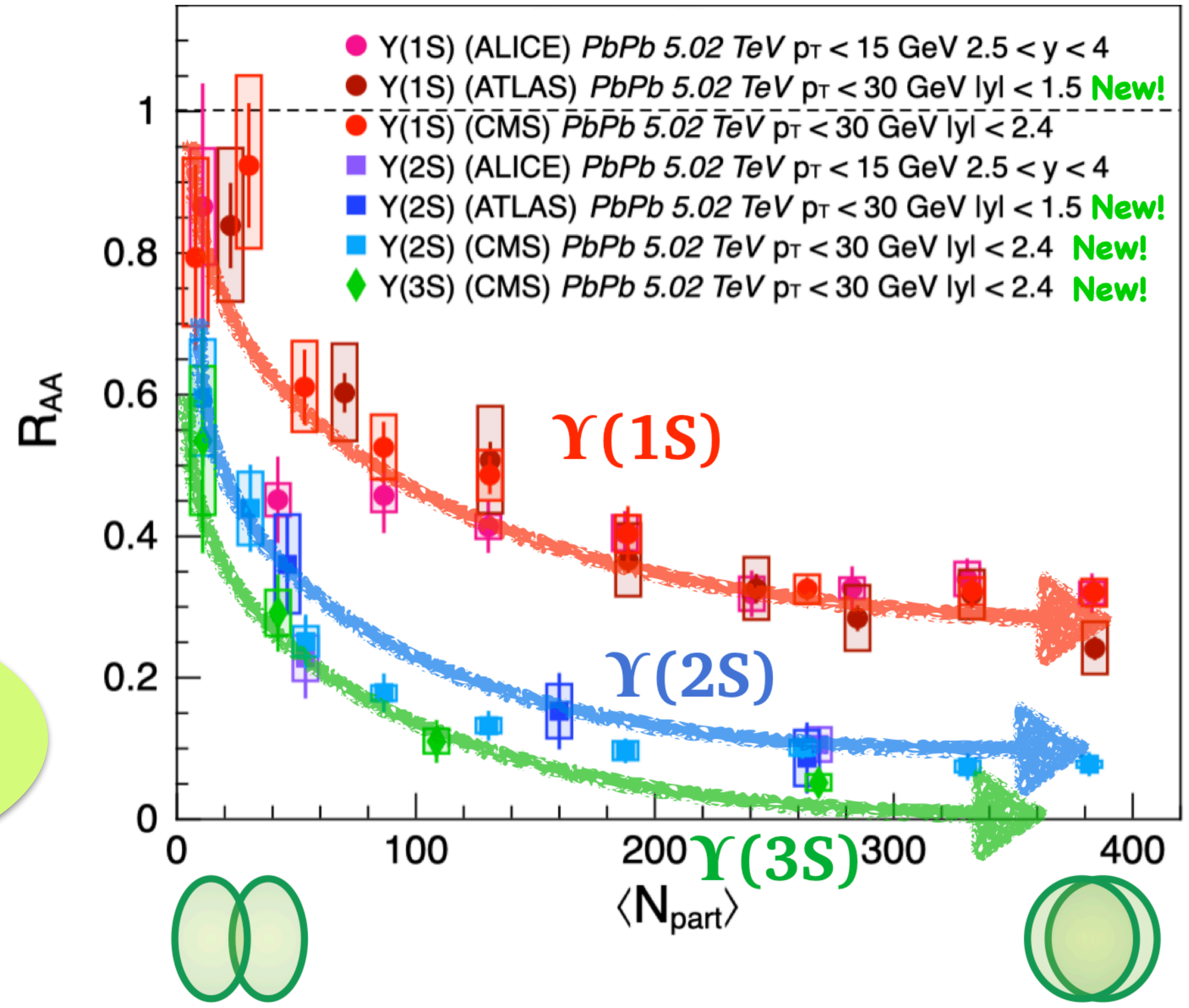


Heavy Quarkonia in heavy-ion collisions

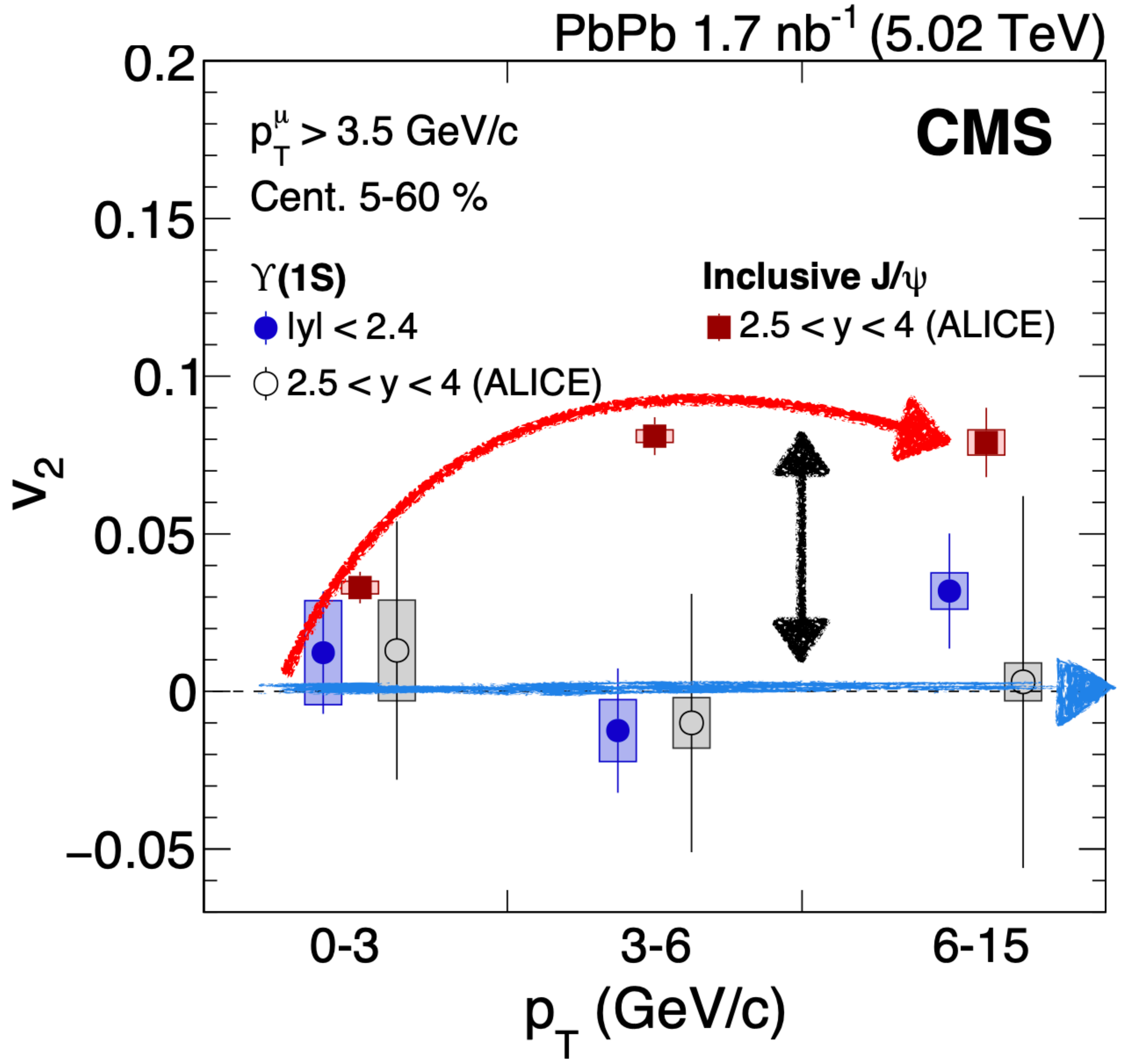
- Heavy quarkonia: Bound states of heavy quark and its anti-quark
  - Powerful tool to study thermal properties of QGP
  - Different binding energies will be modified differently
  - Different dynamics for charmonia and bottomonia

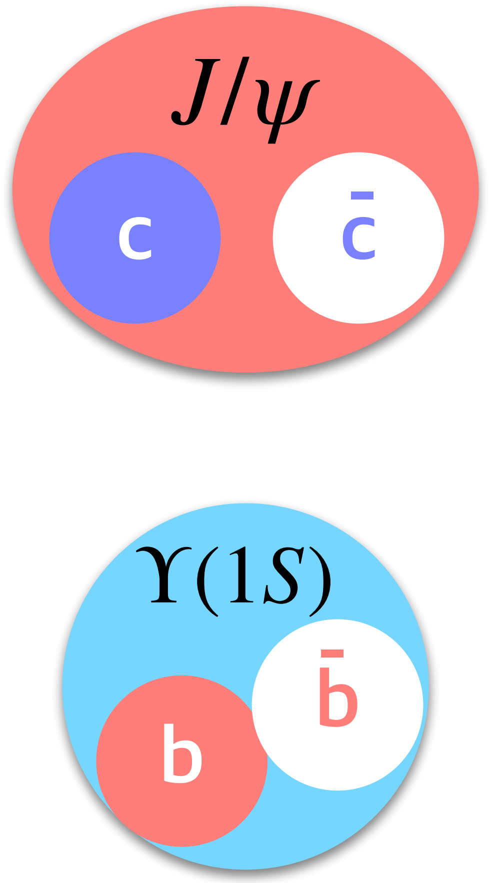


$R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$



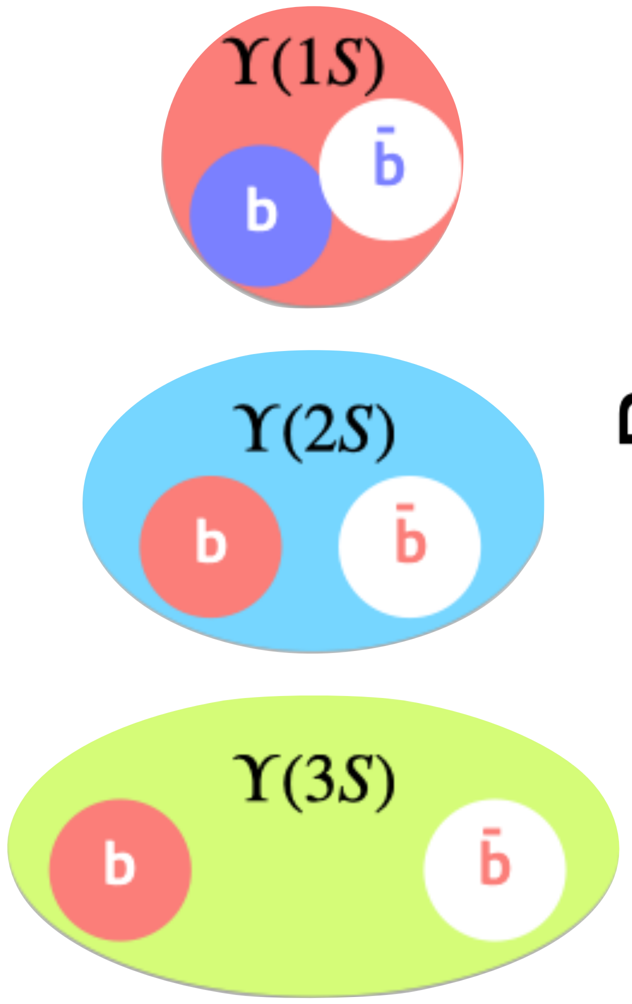
Υ(1S) $v_2 \approx 0$ <—> J/ψ $v_2 > 0$



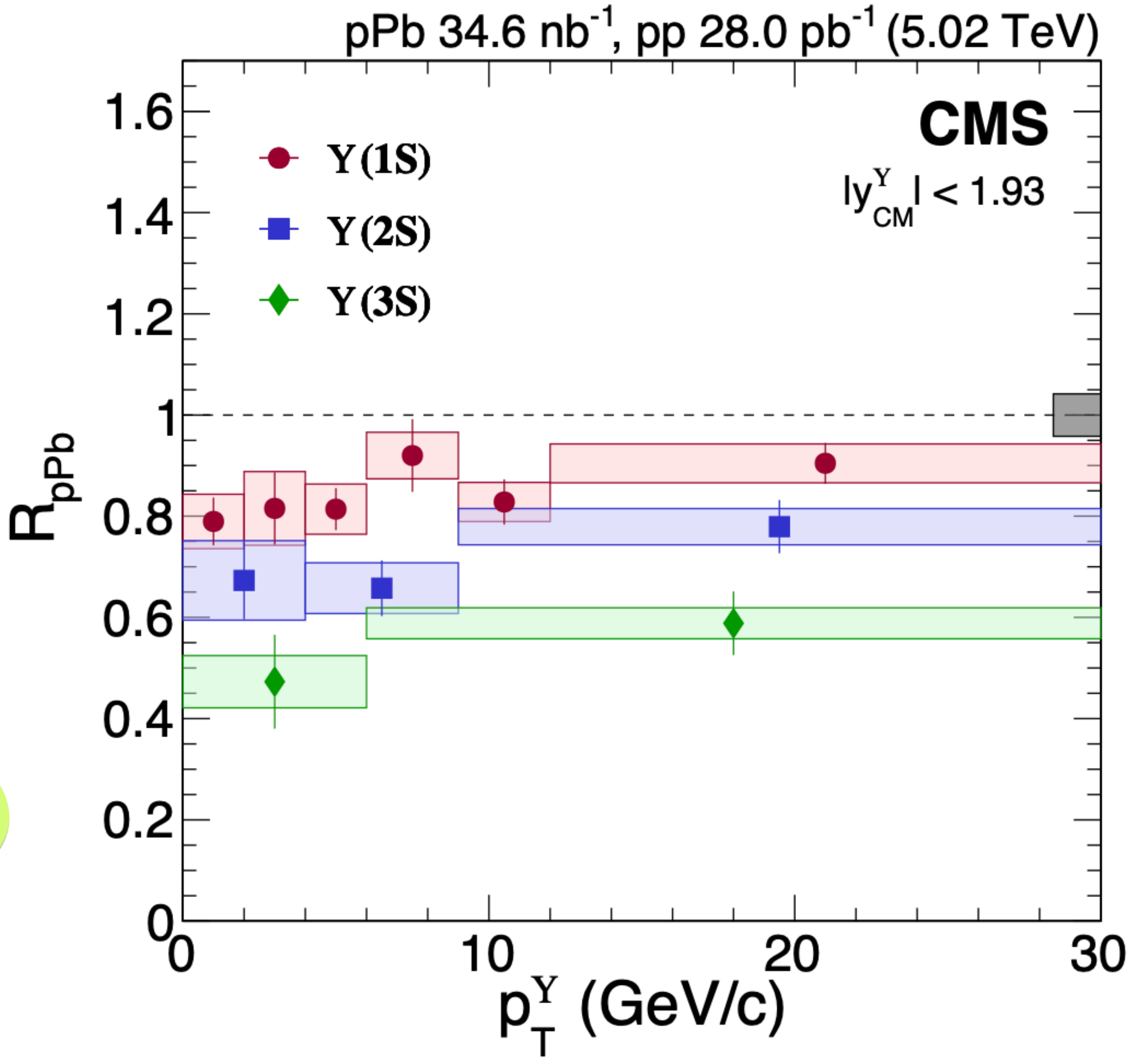


Heavy Quarkonia in small collisions system

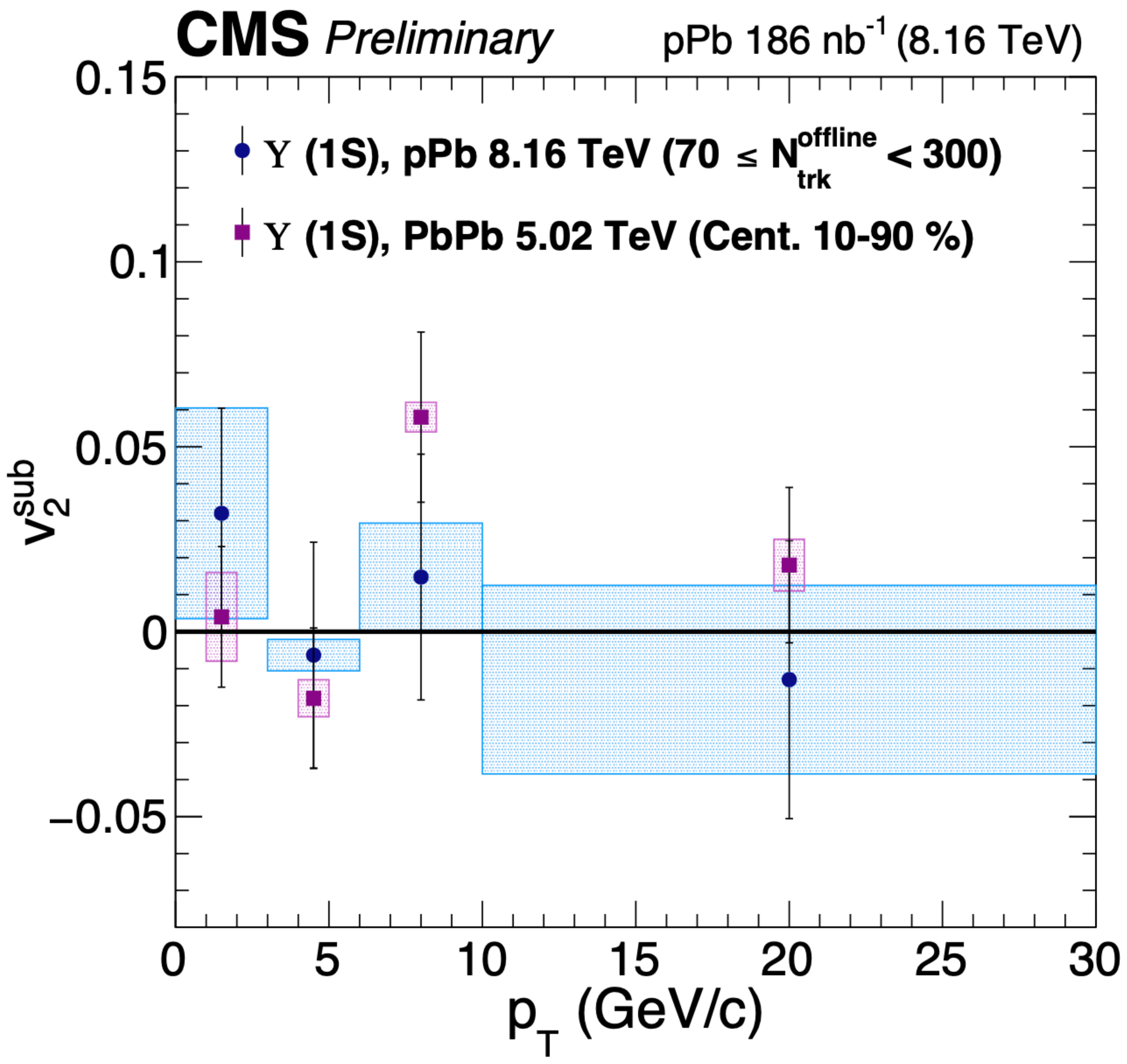
- QGP-like behavior in smaller collision systems!
- Cold Nuclear Matter effects(CNM) on heavy quarkonia
  - PDFs Modification, energy loss or nucleus absorption, and interactions with comoving particles

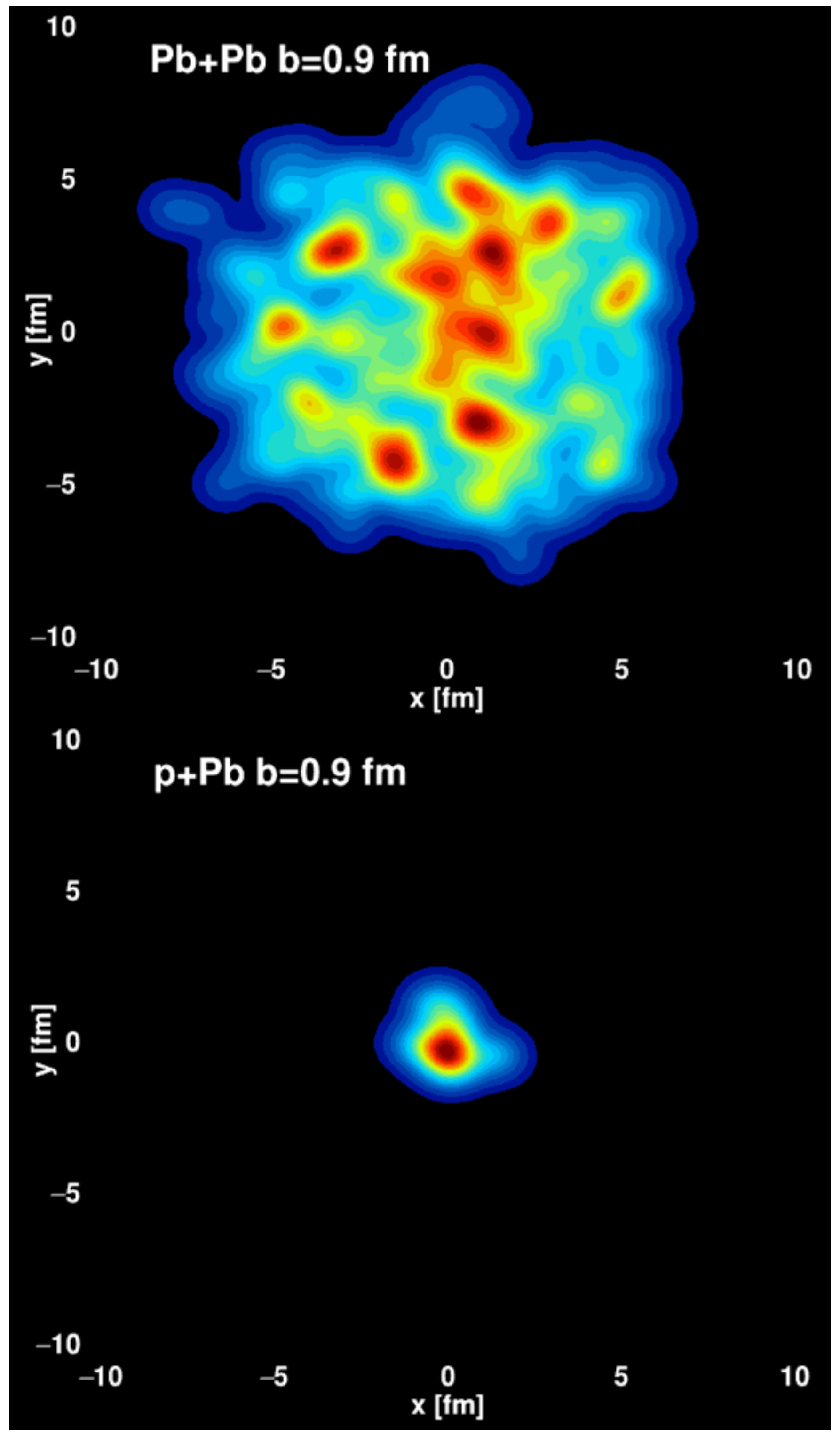


$R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$



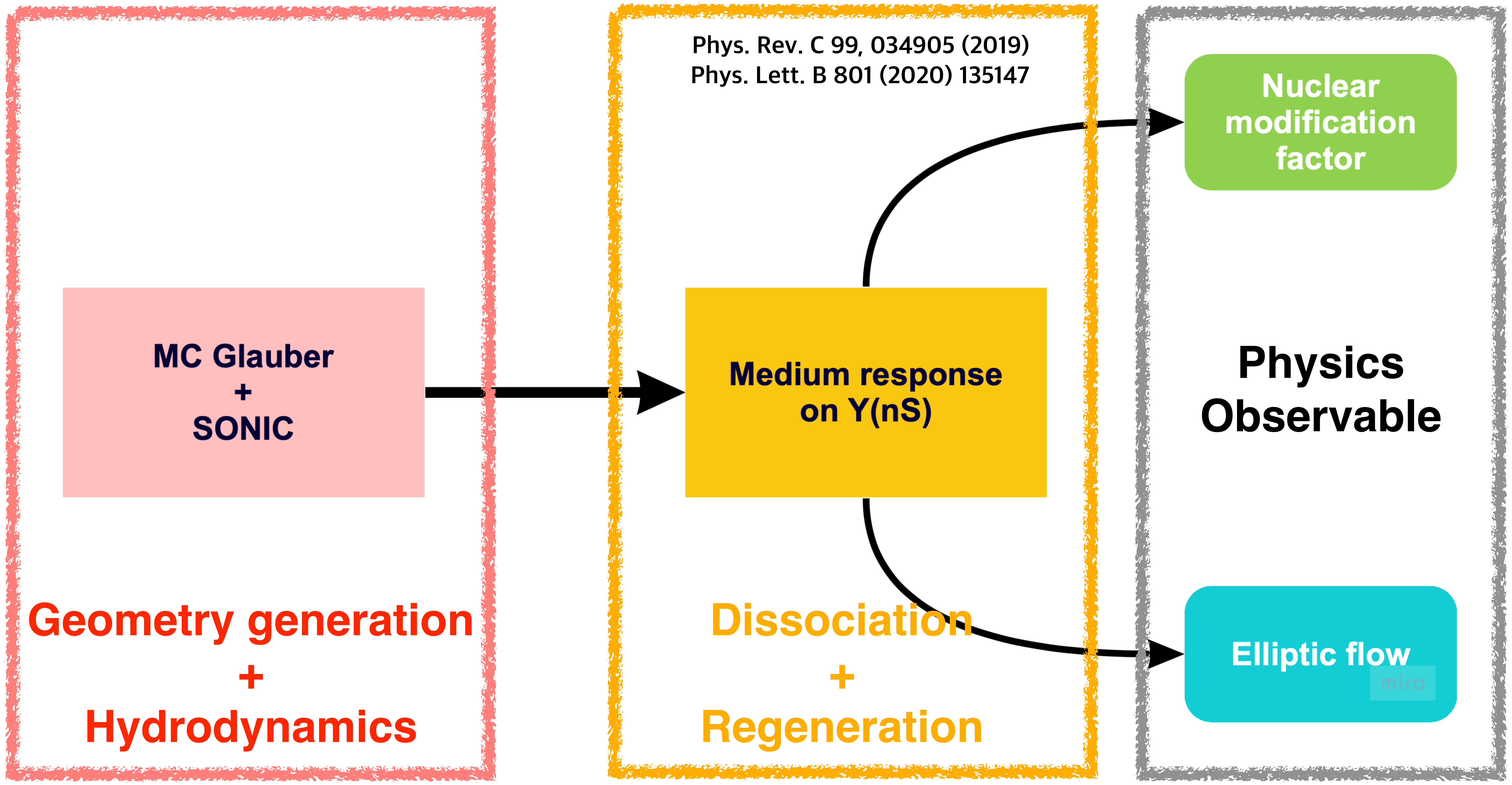
$\Upsilon(1S)\ v_2 \approx 0$





Monte Carlo simulation framework of quarkonia

- Simulation for Heavy IoN Collisionwith Heavy-quark and ONia (SHINCHON) framework



Phys. Rev. C 99, 034905 (2019)
Phys. Lett. B 801 (2020) 135147

MC Glauber
+
SONIC

Medium response on Y(nS)

Nuclear modification factor

Physics Observable

Elliptic flow

Geometry generation
+
Hydrodynamics

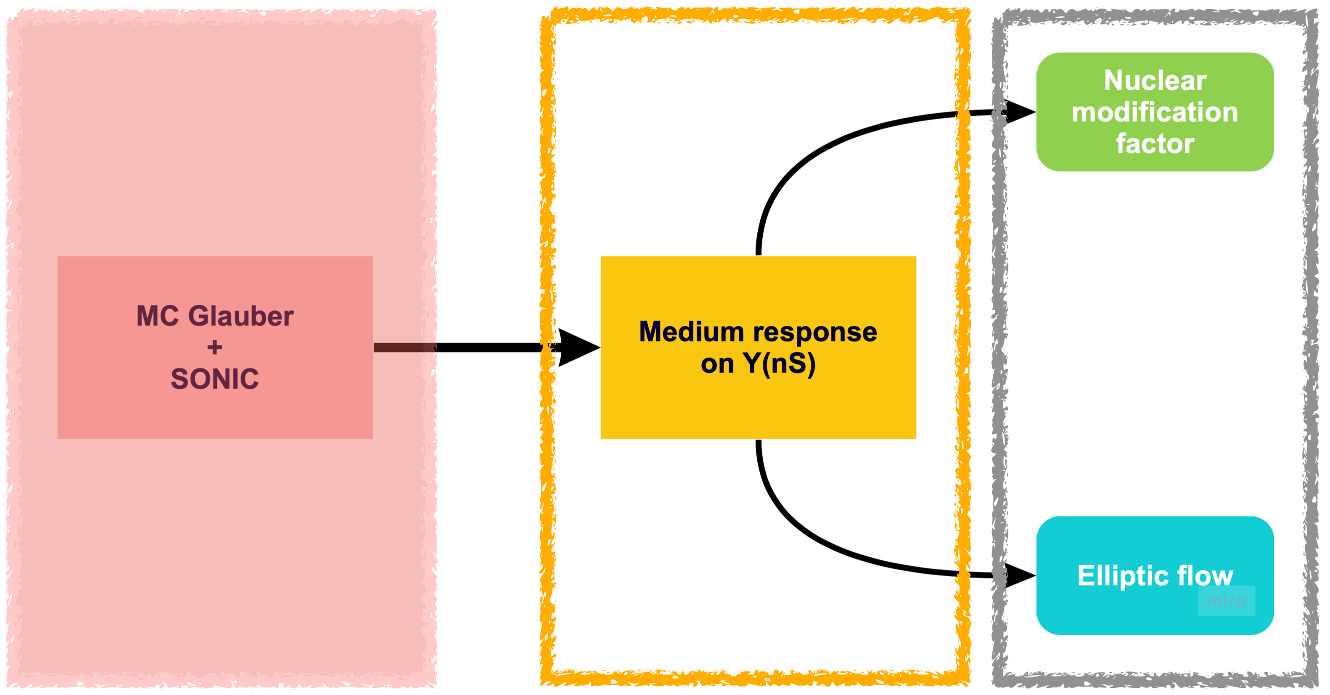
Dissociation
+
Regeneration

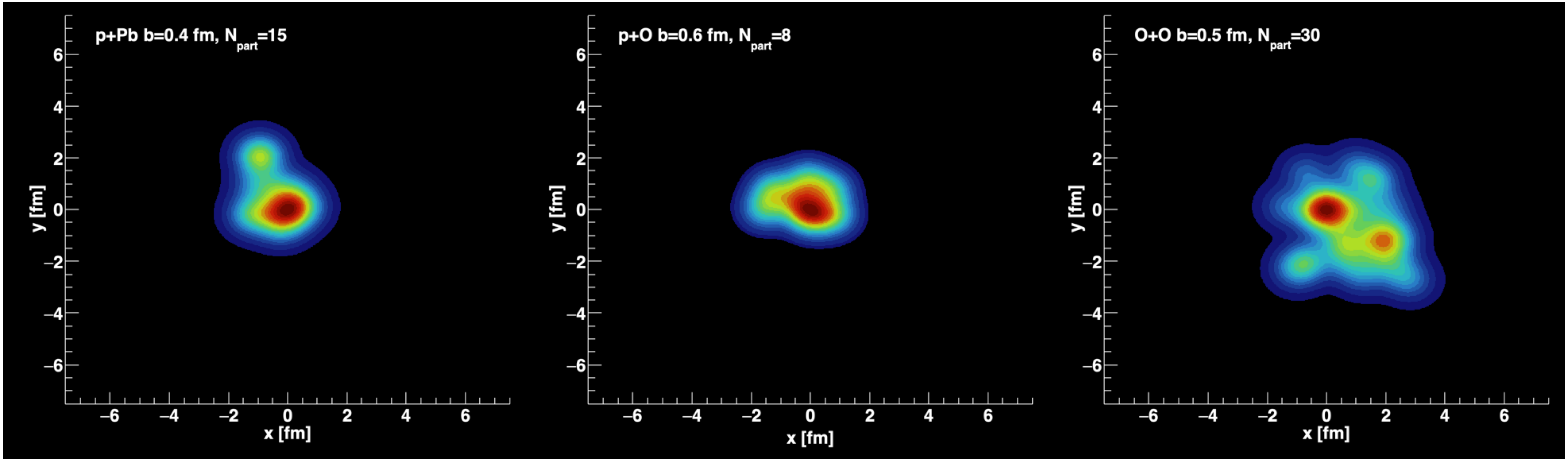
$$R_{pA} = \frac{1}{A}\frac{d\sigma_{pA}/dp_T}{d\sigma_{pp}/dp_T}$$

$$\frac{dN}{d(\phi - \Psi)} \propto 1 + 2v_2 cos(2(\phi - \Psi))$$

Monte Carlo simulation framework of quarkonia

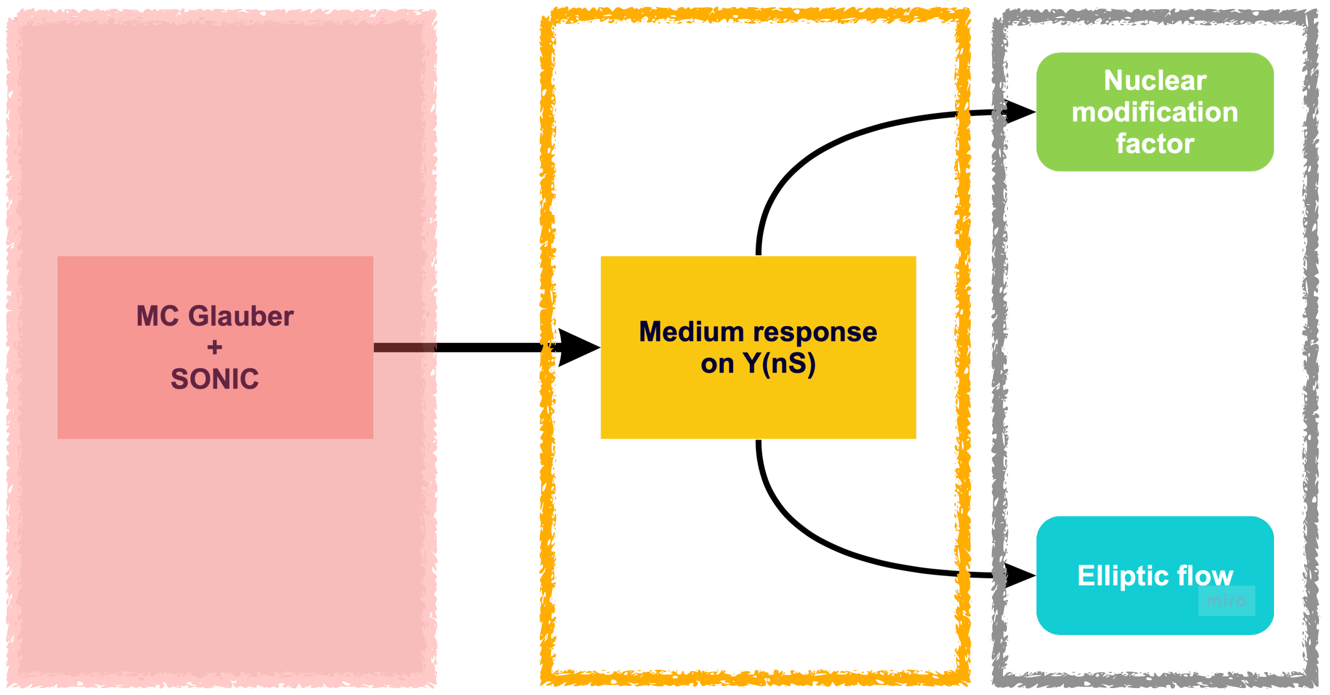
- Geometry generator: **MC Glauber** framework
  - Collision system: p+Pb, p+O, O+O at $\sqrt{s_{NN}} = 8$ TeV
  - Nucleon-nucleon inelastic cross section: 72 mb
  - Gaussian of width for energy deposition of nucleon: 0.4 fm





Monte Carlo simulation framework of quarkonia

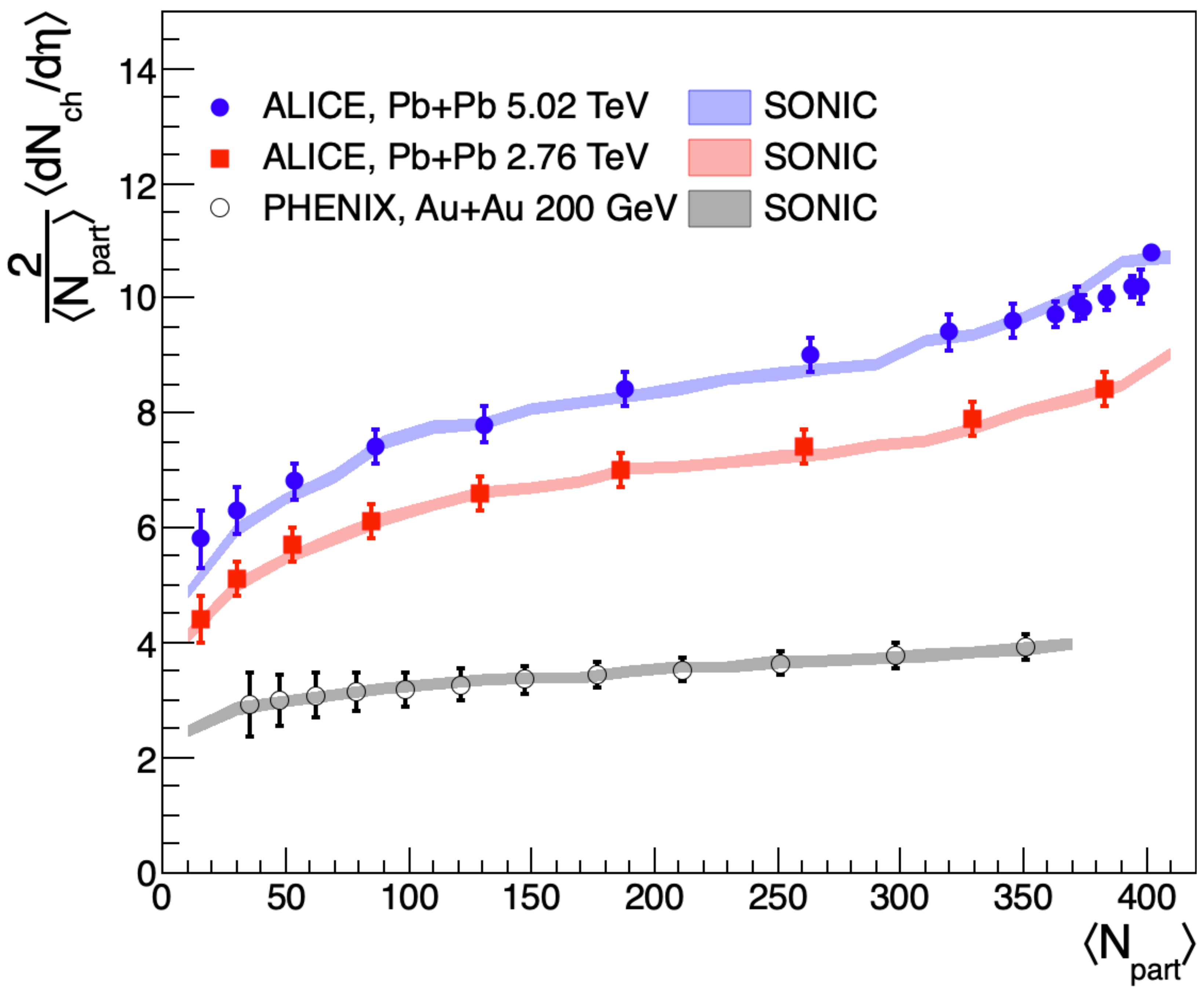
- Hydrodynamic simulation: **SONIC** framework
  - $\eta/s = 0.08$ & $\varsigma/s = 0$
- The deposited energy distributions are scaled based on the charged particle multiplicity at mid-rapidity in p+Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV
  - **Assumption**: The scale factor does not change much in the collision systems with a similar number of participants

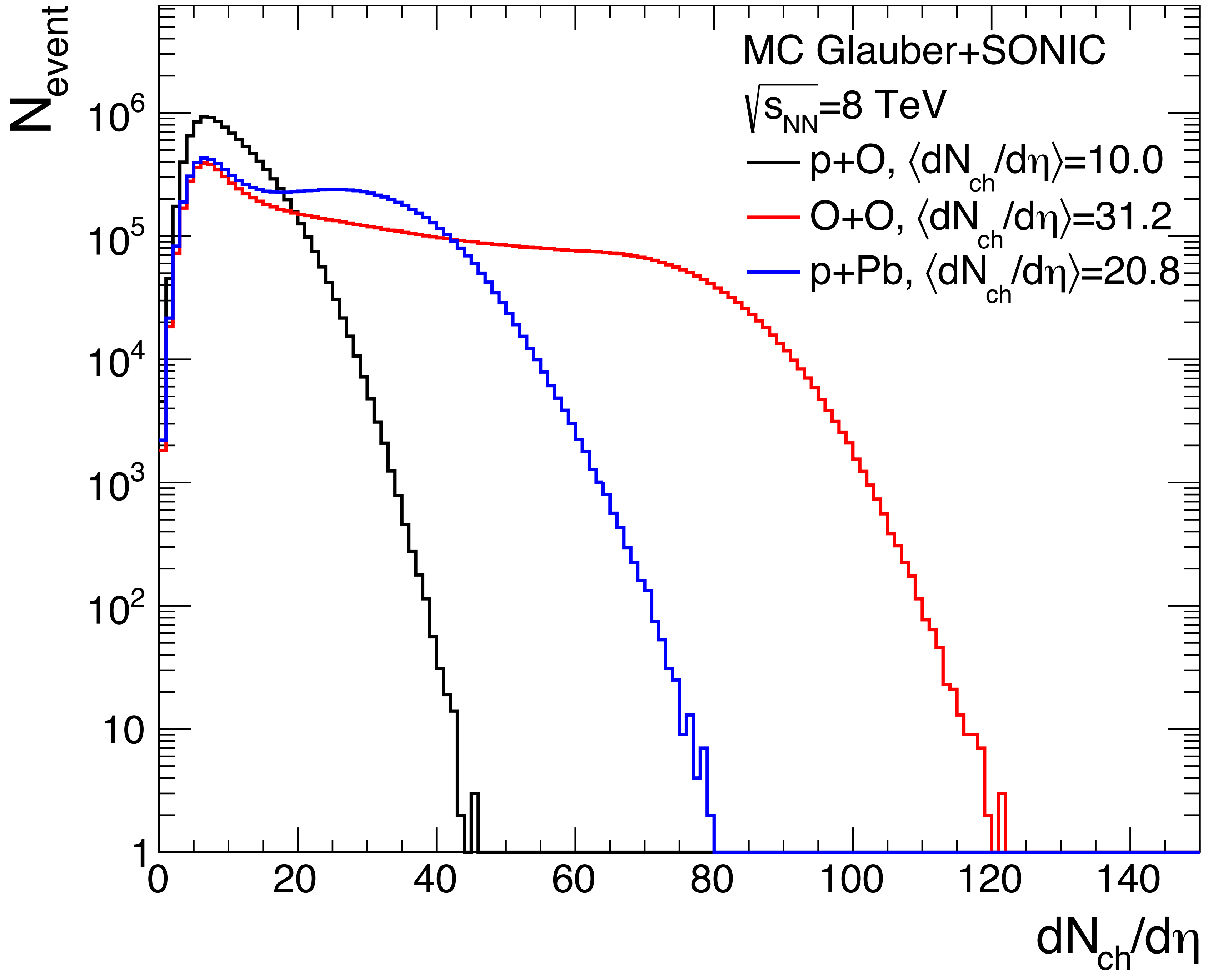

MC Glauber + SONIC

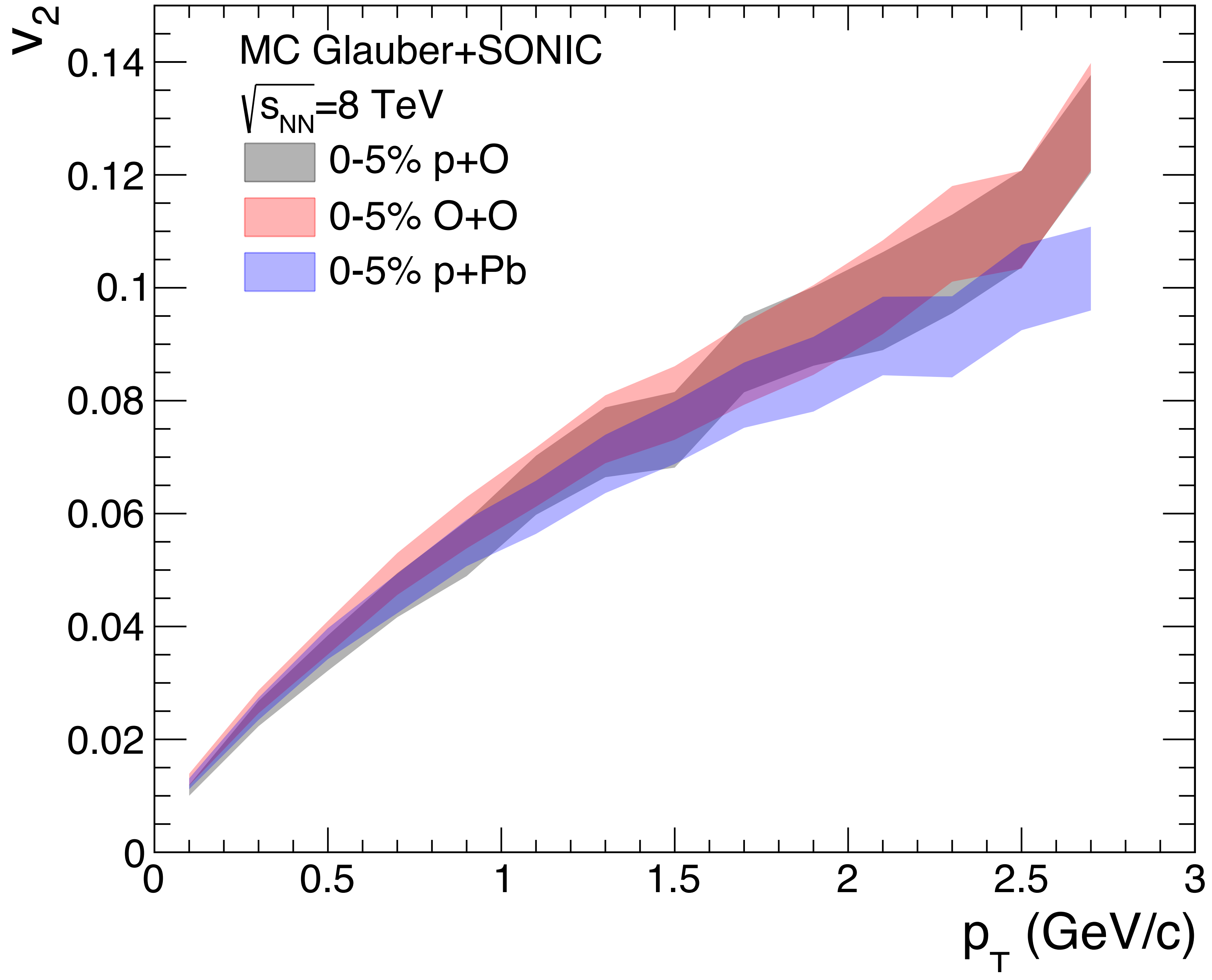
Medium response on Y(nS)

Nuclear modification factor

Elliptic flow

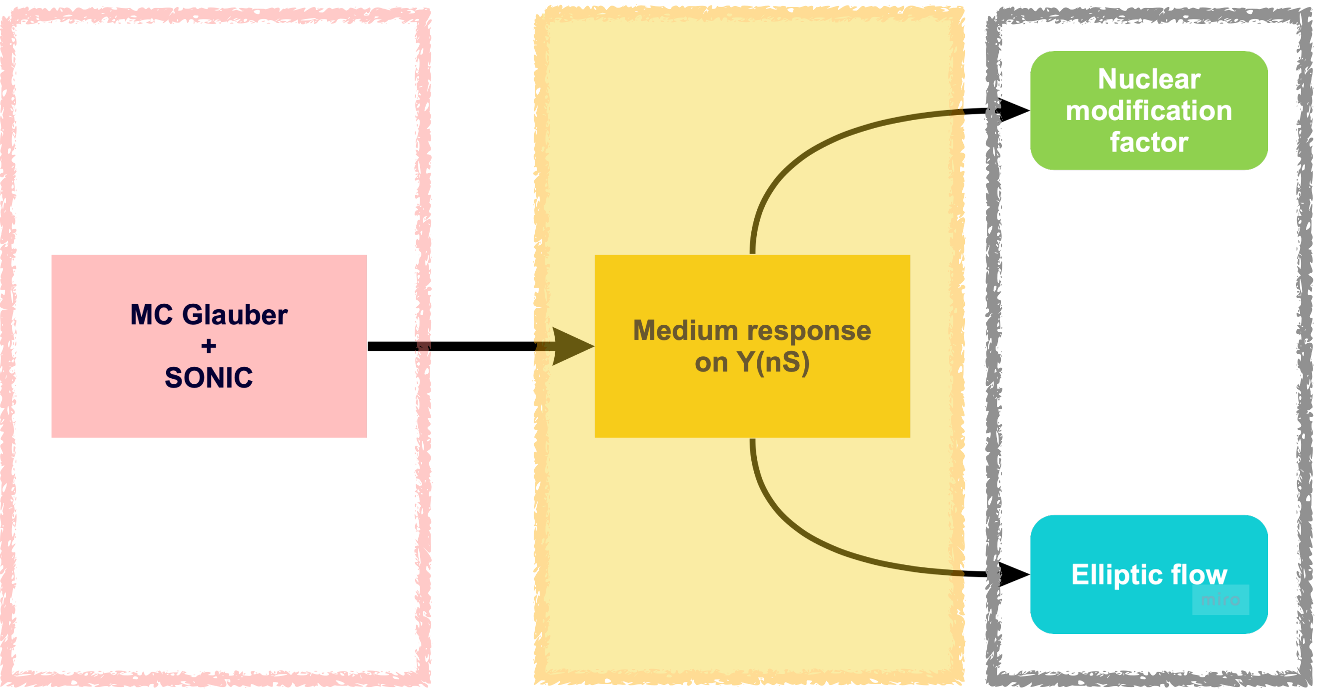






Monte Carlo simulation framework of quarkonia

- Medium response on Upsilon: Gluo-dissociation + Inelastic Parton scattering

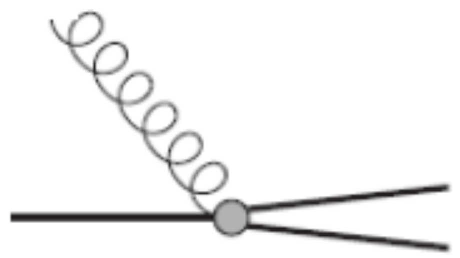

MC Glauber + SONIC

Medium response on Y(nS)

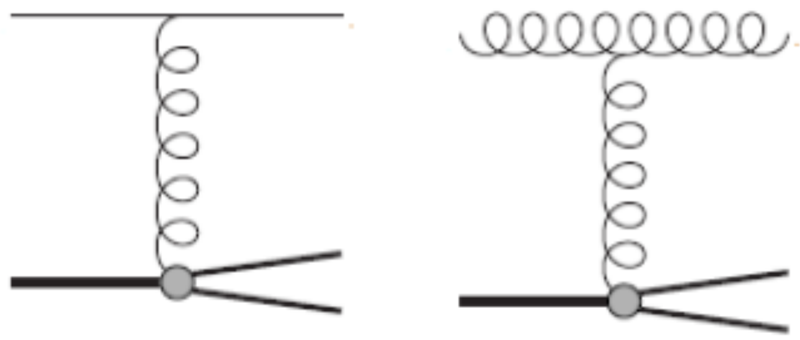
Nuclear modification factor

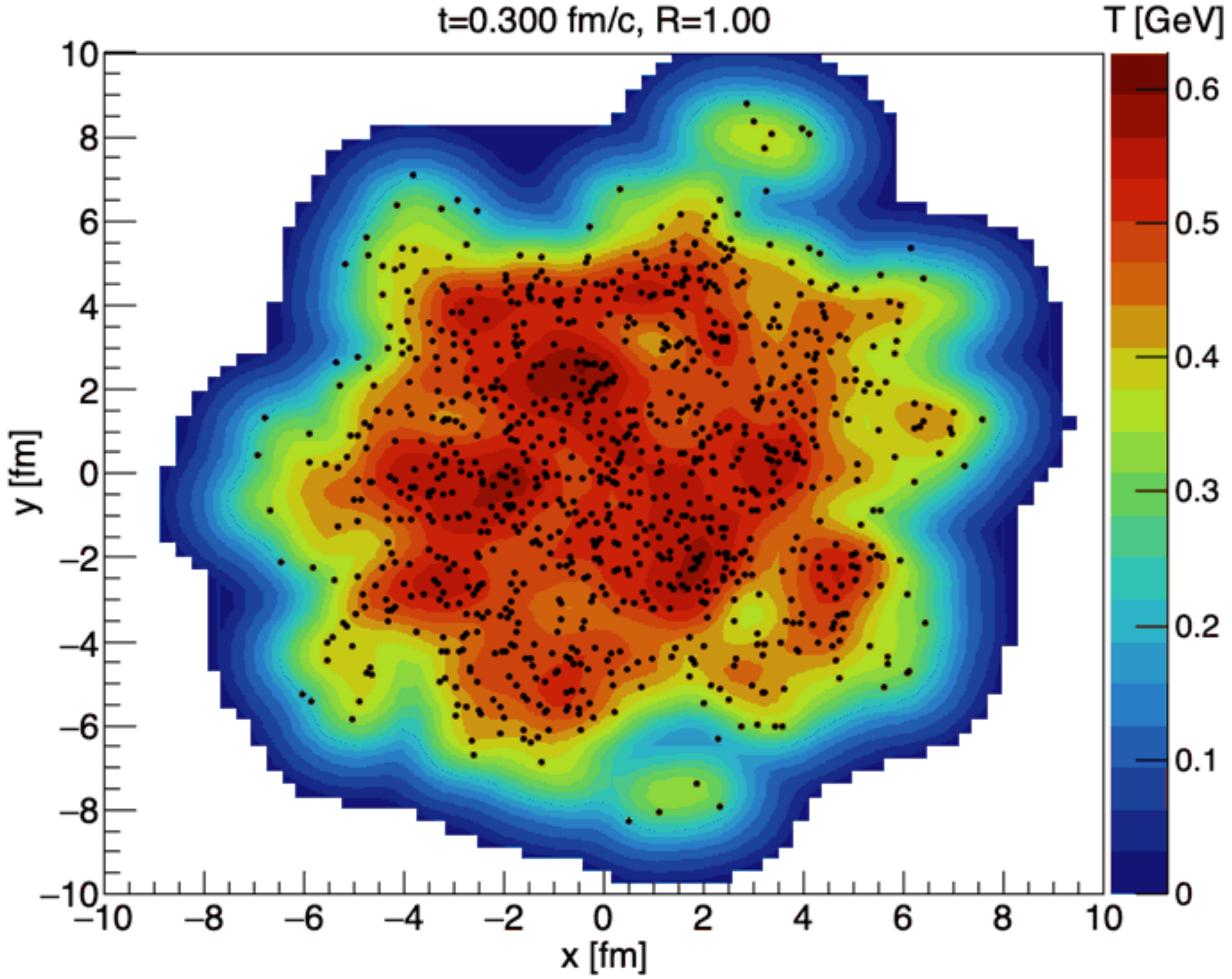
Elliptic flow

- Gluo-dissociation (LO)

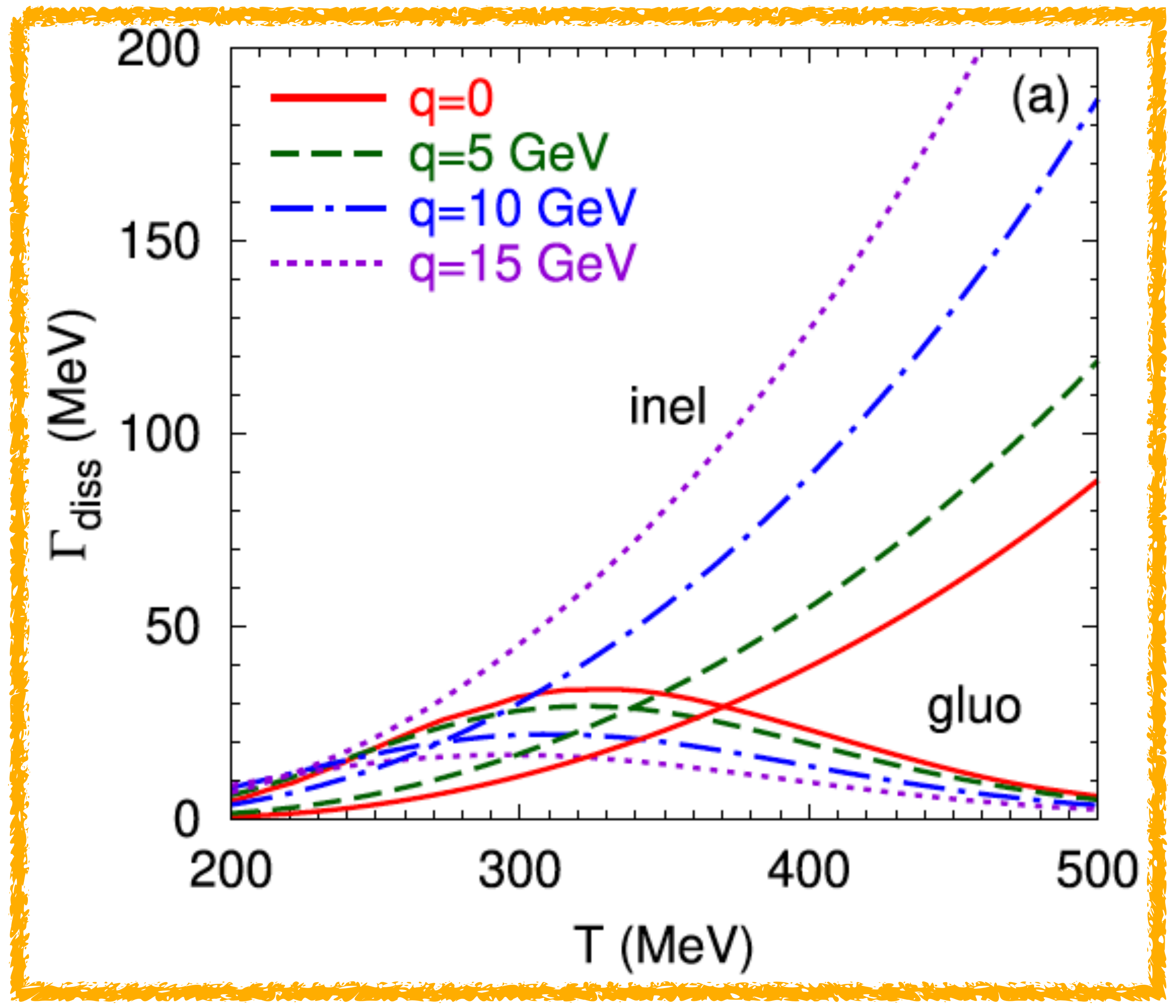


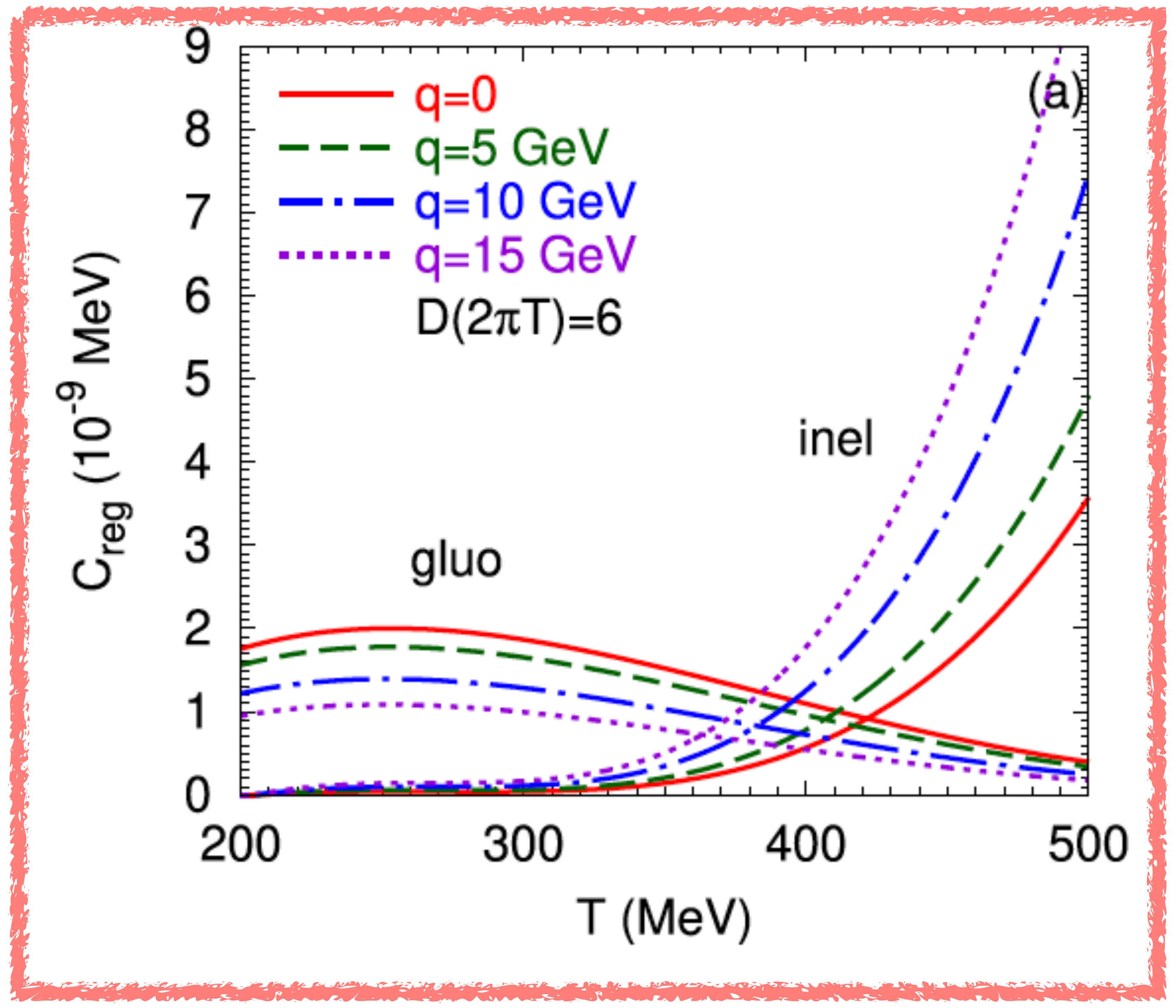
- Inelastic parton scattering (NLO)



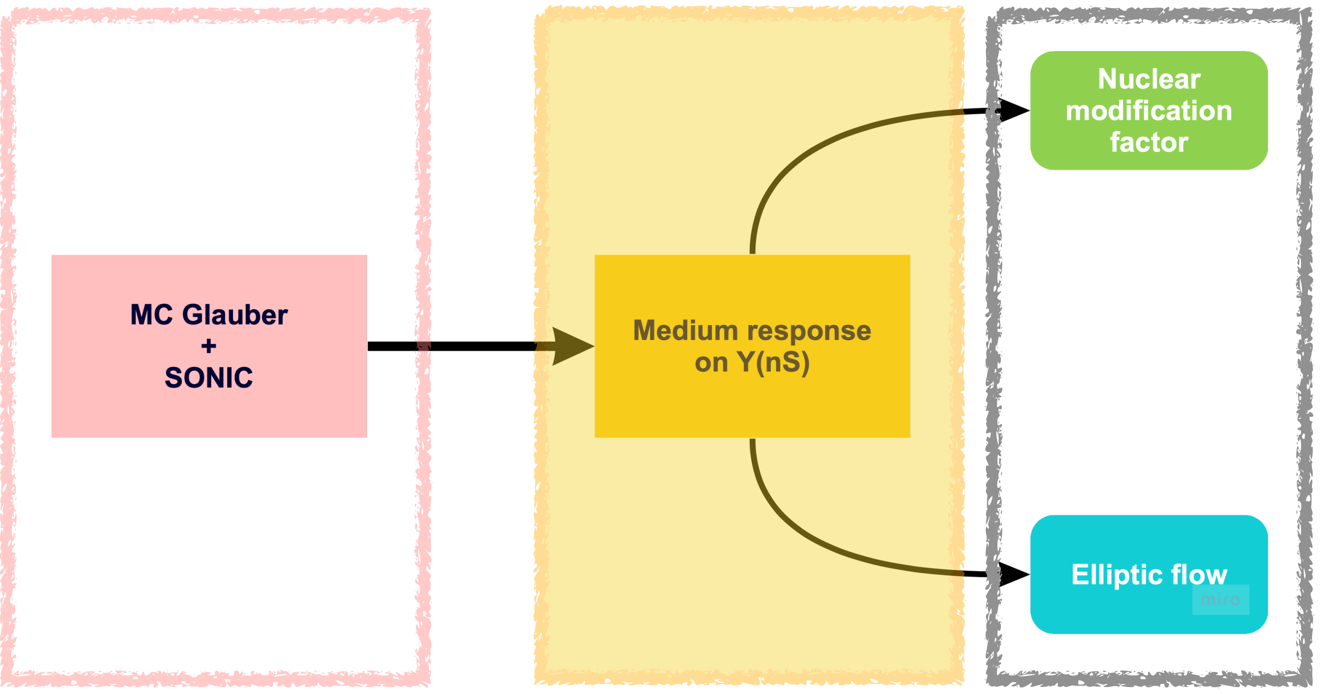


$$(\frac{\partial}{\partial \mathrm{t}} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{x}}) \mathrm{f}_\Upsilon(\mathrm{t},\mathbf{x},\mathbf{q}) = -\Gamma^{\mathrm{gluo+inel}}_{\mathrm{diss}}(\mathrm{t},\mathbf{x},\mathbf{q})\mathrm{f}_\Upsilon(\mathrm{t},\mathbf{x},\mathbf{q}) + \mathrm{C}^{\mathrm{gluo+inel}}_{\mathrm{reg}}(\mathrm{t},\mathbf{x},\mathbf{q})[\mathrm{f}_\mathrm{b}, \mathrm{f}_{\bar{\mathrm{b}}}](\mathrm{t},\mathbf{x},\mathbf{q})$$

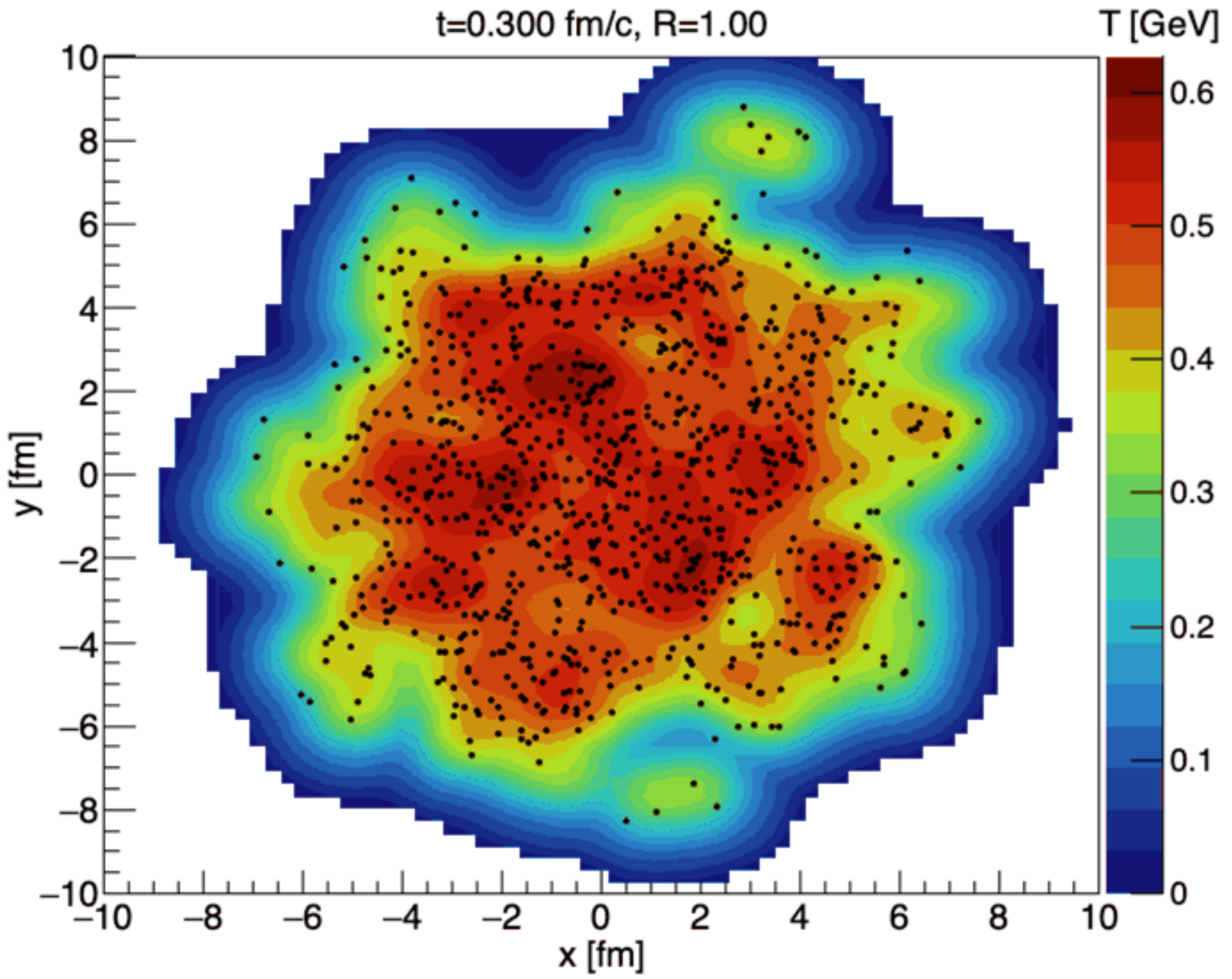




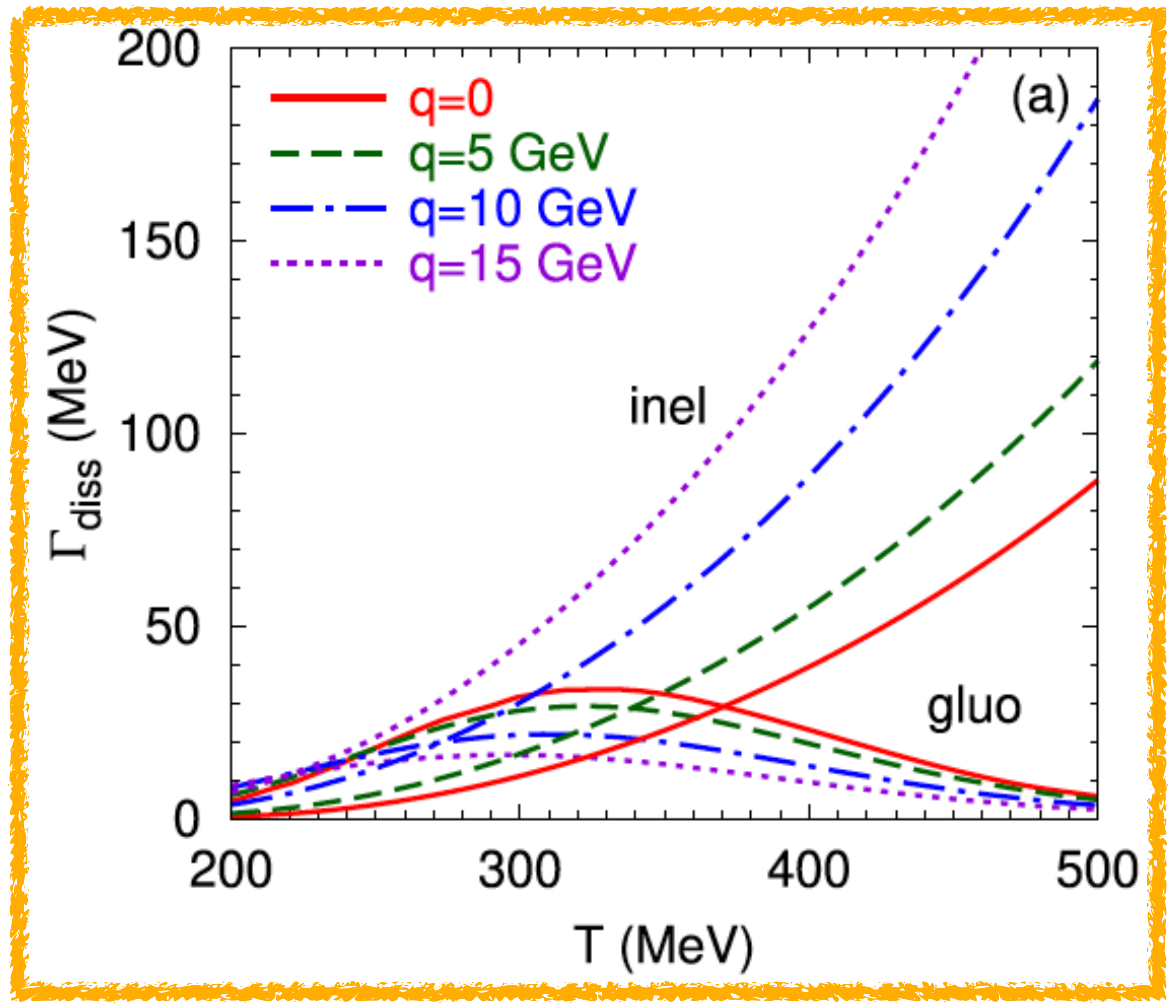
Monte Carlo simulation framework of quarkonia


MC Glauber + SONIC
Medium response on Y(nS)
Nuclear modification factor
Elliptic flow

- Medium response on Upsilon: Gluo-dissociation + Inelastic Parton scattering
  - **Only** **dissociation** **effect** is considered
- Survival fraction of Upsilons for certain time step(Δt): $\dfrac{N(t+\Delta t, p_T)}{N(t, p_T)} = e^{-\int_t^{t+\Delta t}} dt'\,\Gamma_{diss}(t', p_T)$
- Tsallis fit to p_T distribution fo Υ(1S) in Pb+Pb $\sqrt{s_{NN}}$ = 5.02 TeV

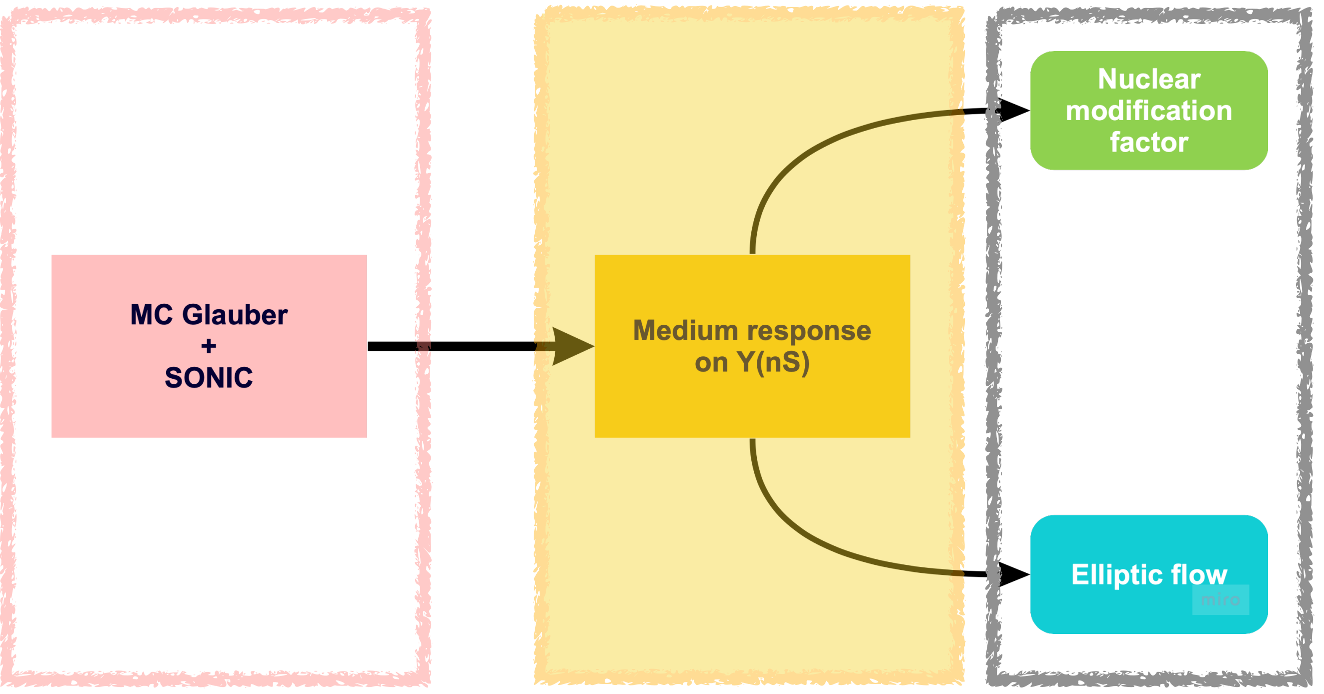


$$\left(\frac{\partial}{\partial \mathrm{t}} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{x}}\right)\mathrm{f}_{\Upsilon}(\mathrm{t},\mathbf{x},\mathbf{q}) = -\Gamma^{\mathrm{gluo+inel}}_{\mathrm{diss}}(\mathrm{t},\mathbf{x},\mathbf{q})\mathrm{f}_{\Upsilon}(\mathrm{t},\mathbf{x},\mathbf{q}) + \mathrm{C}^{\mathrm{gluo+inel}}_{\mathrm{reg}}(\mathrm{t},\mathbf{x},\mathbf{q})[\mathrm{f}_{\mathrm{b}},\mathrm{f}_{\bar{\mathrm{b}}}](\mathrm{t},\mathbf{x},\mathbf{q})$$



Regeneration effect expected to be negligible in small system

Monte Carlo simulation framework of quarkonia


MC Glauber + SONIC

Medium response on Υ(nS)

Nuclear modification factor

Elliptic flow

- Medium response on Upsilon: Gluo-dissociation + Inelastic Parton scattering
  - **Only** **dissociation effect** is considered
- Survival fraction of Upsilons for certain time step(Δt): $\frac{N(t+\Delta t, p_T)}{N(t, p_T)} = e^{-\int_t^{t+\Delta t}} dt'\, \Gamma_{diss}(t', p_T)$
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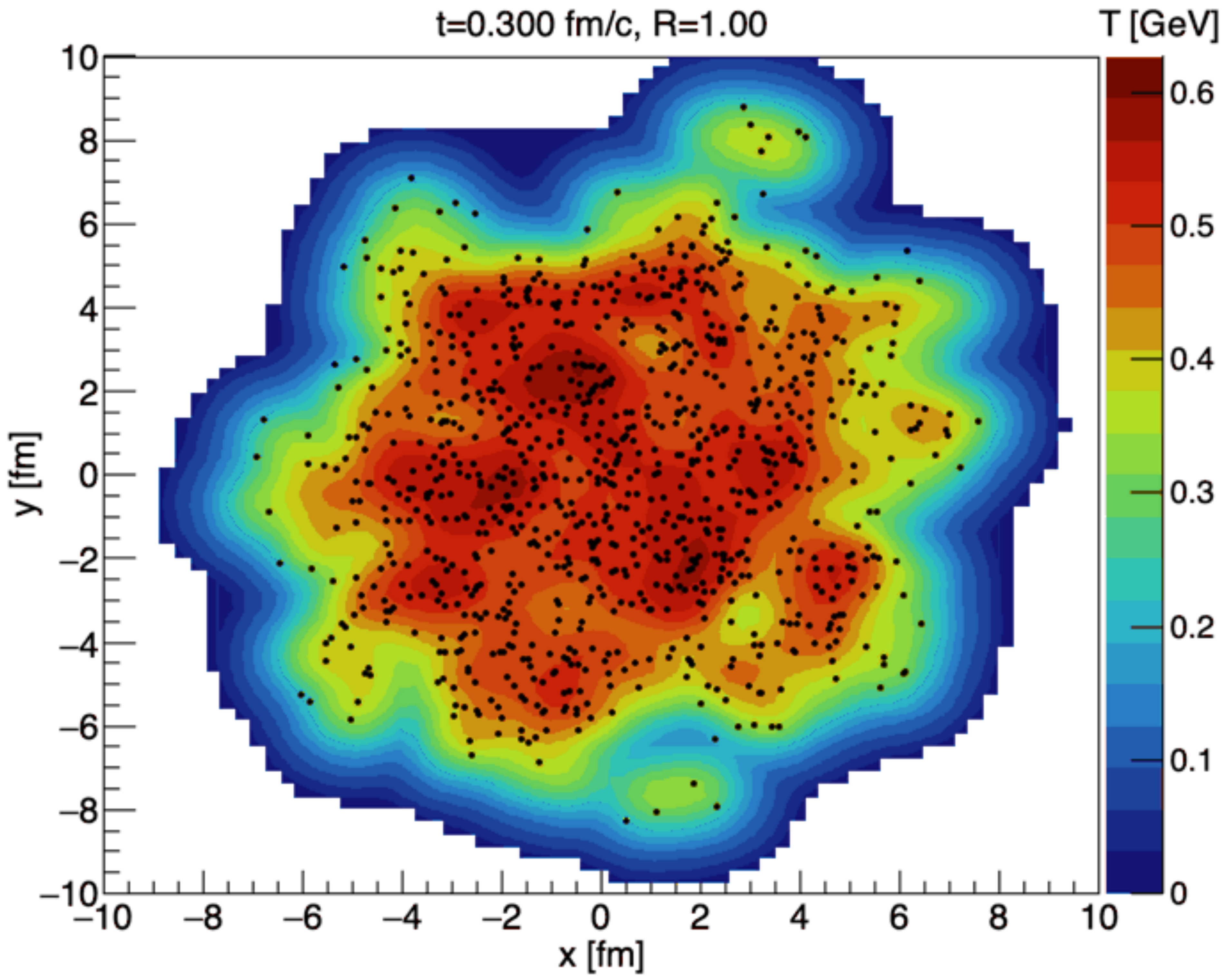
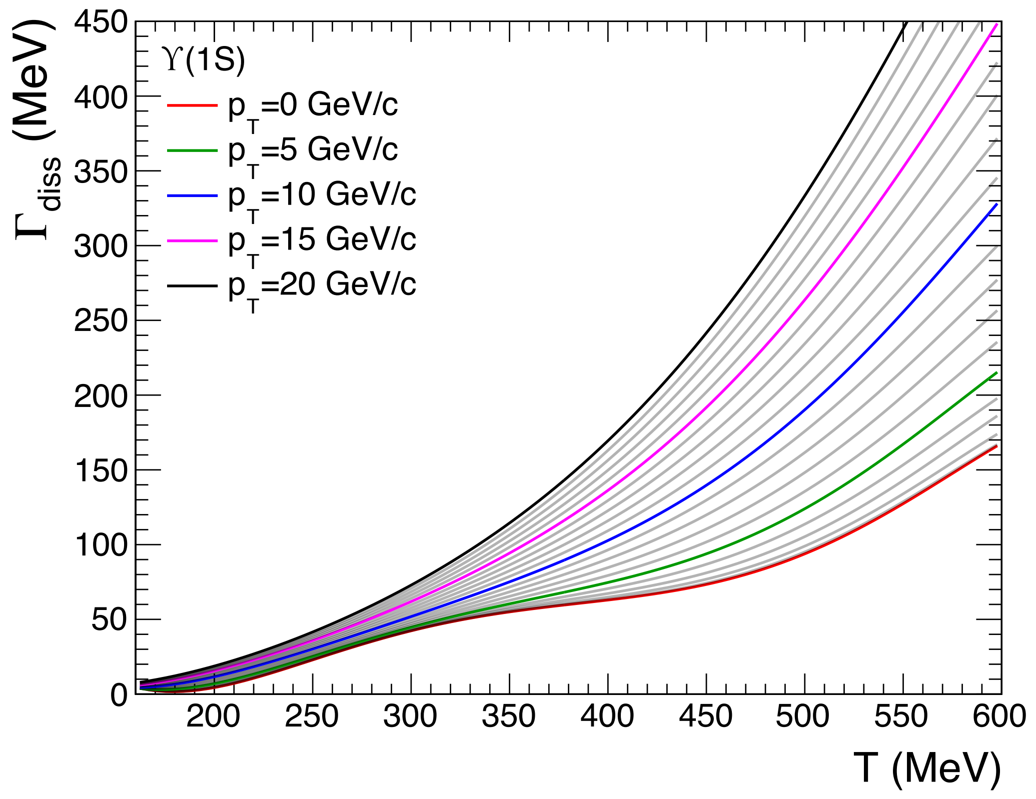
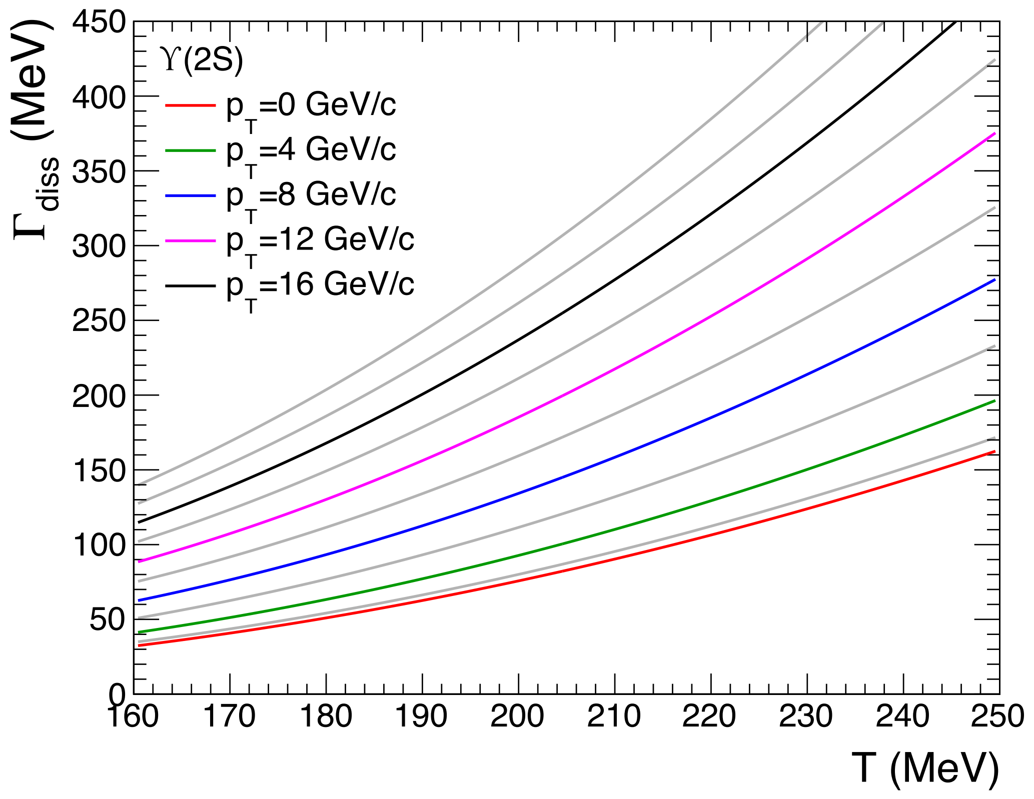
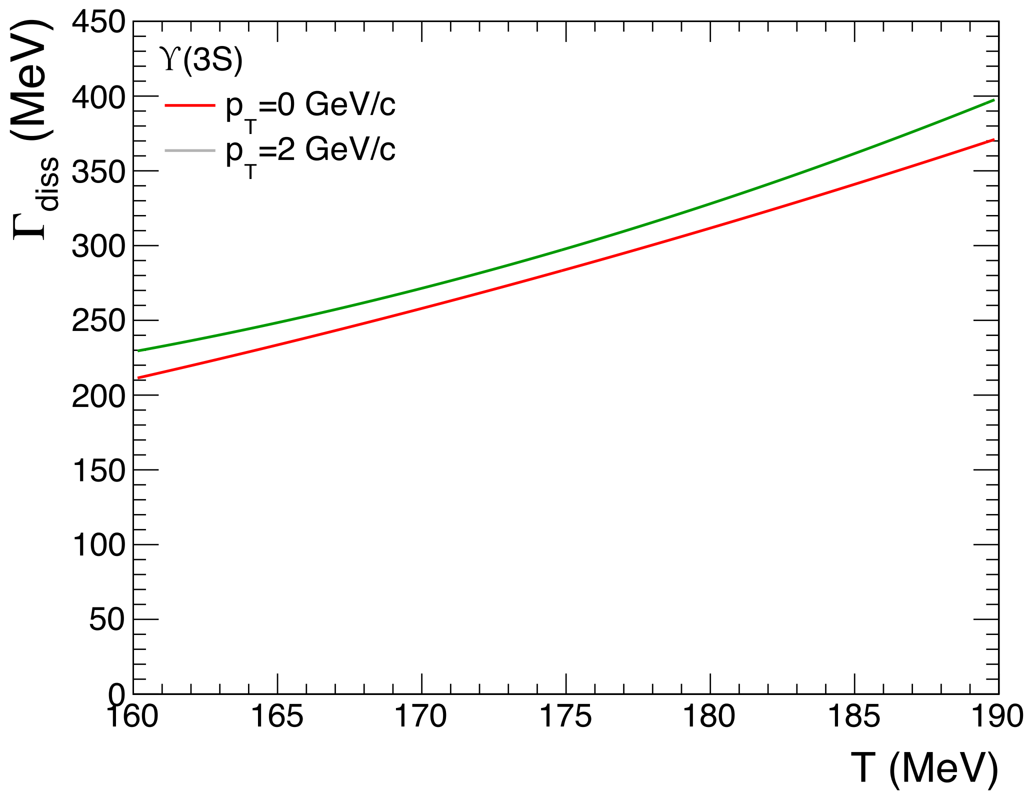


- Fully disassociated temperatures: 600(Υ(1S)), 240(Υ(2S)), and 190(Υ(3S)) MeV
- Formation time: 0.5(Υ(1S)), 1.0(Υ(2S)), and 1.5(Υ(3S)) fm
- $\Gamma_{diss}^{\Upsilon(3S)}(p_T) = \Gamma_{diss}^{\Upsilon(3S)}(2\,\mathrm{GeV/c}) \frac{\Gamma_{\mathrm{diss}}^{\Upsilon(2S)}(\mathrm{p_T})}{\Gamma_{\mathrm{diss}}^{\Upsilon(2S)}(2\,\mathrm{GeV/c})}$

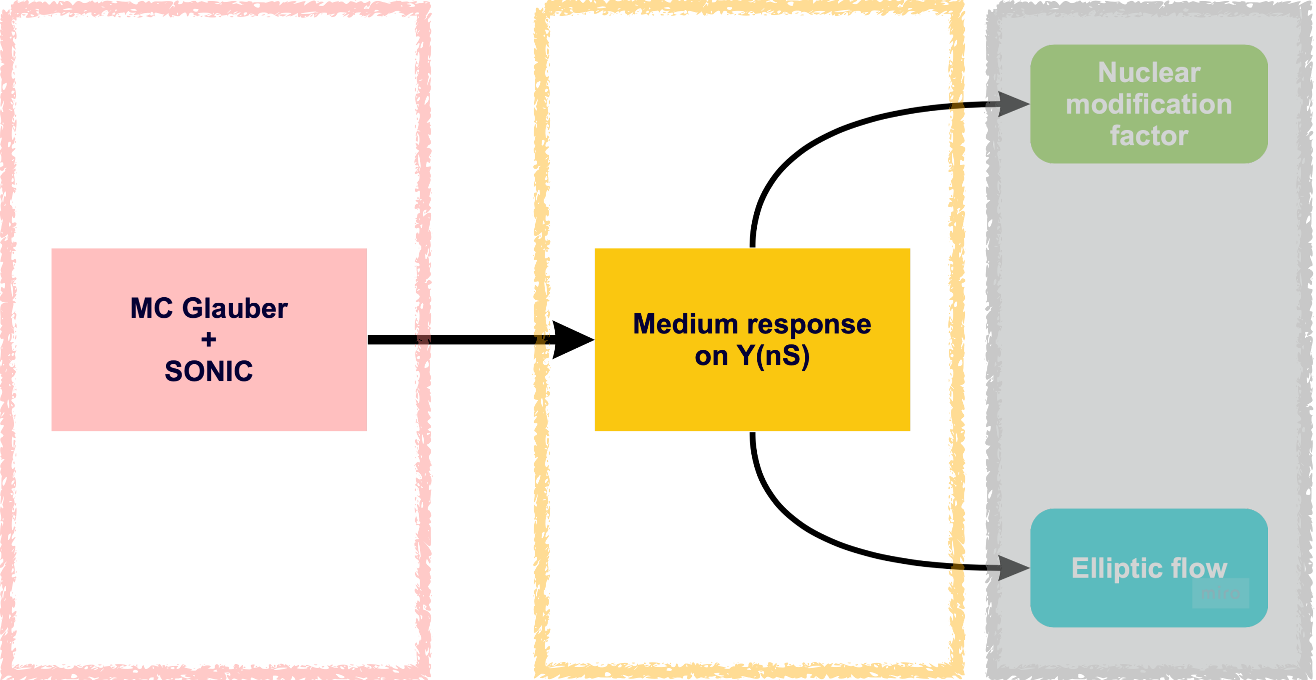


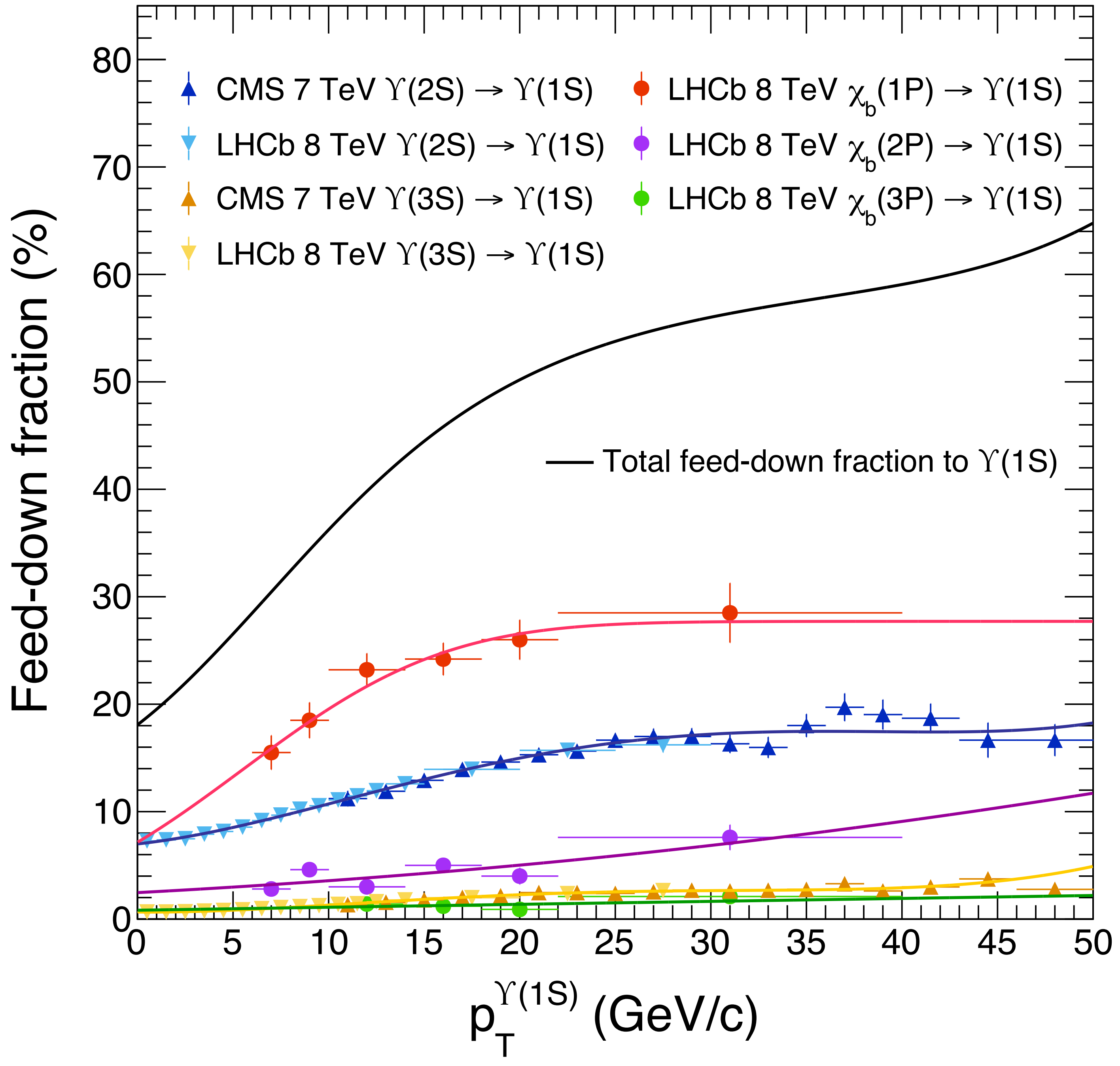


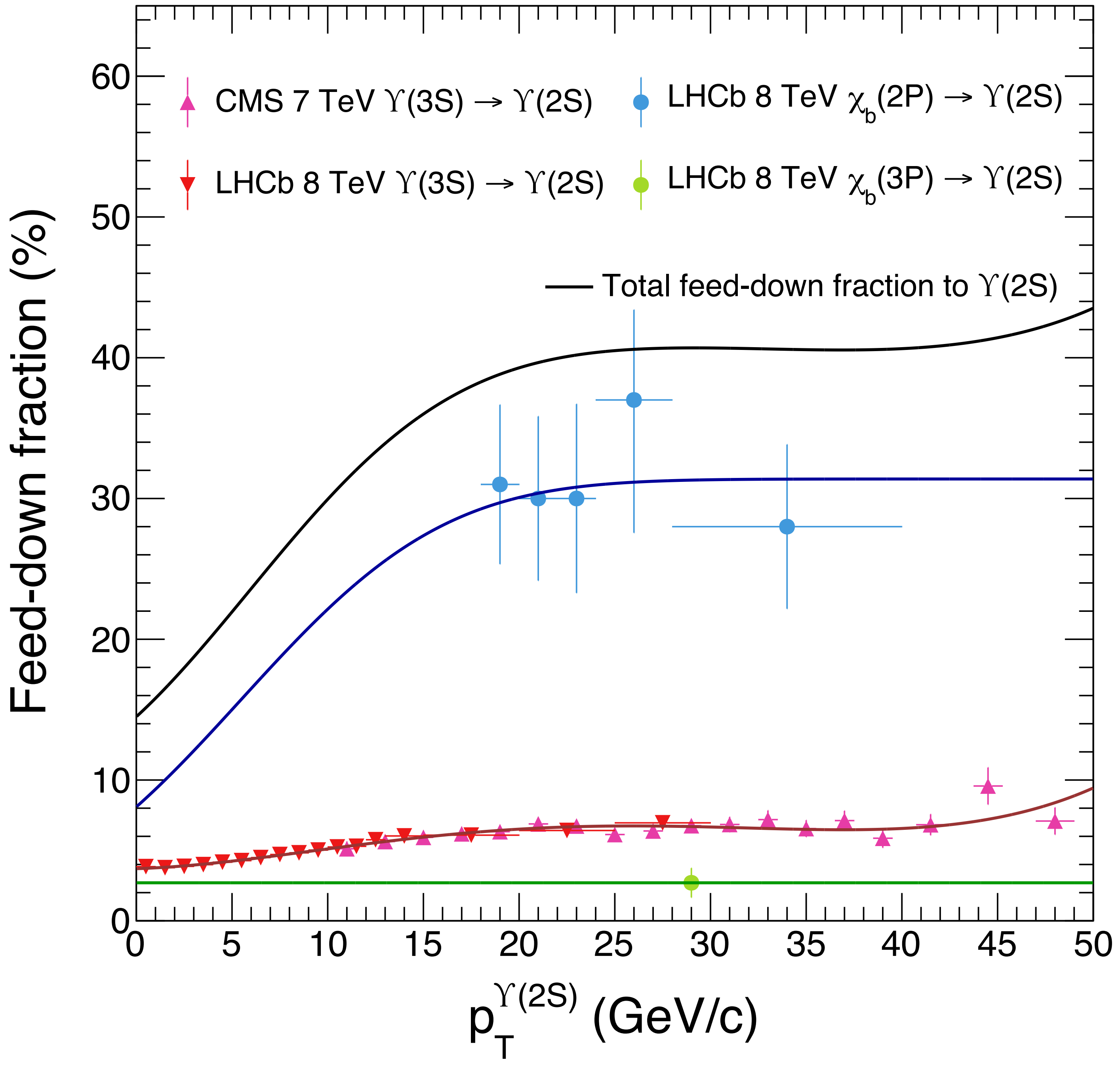


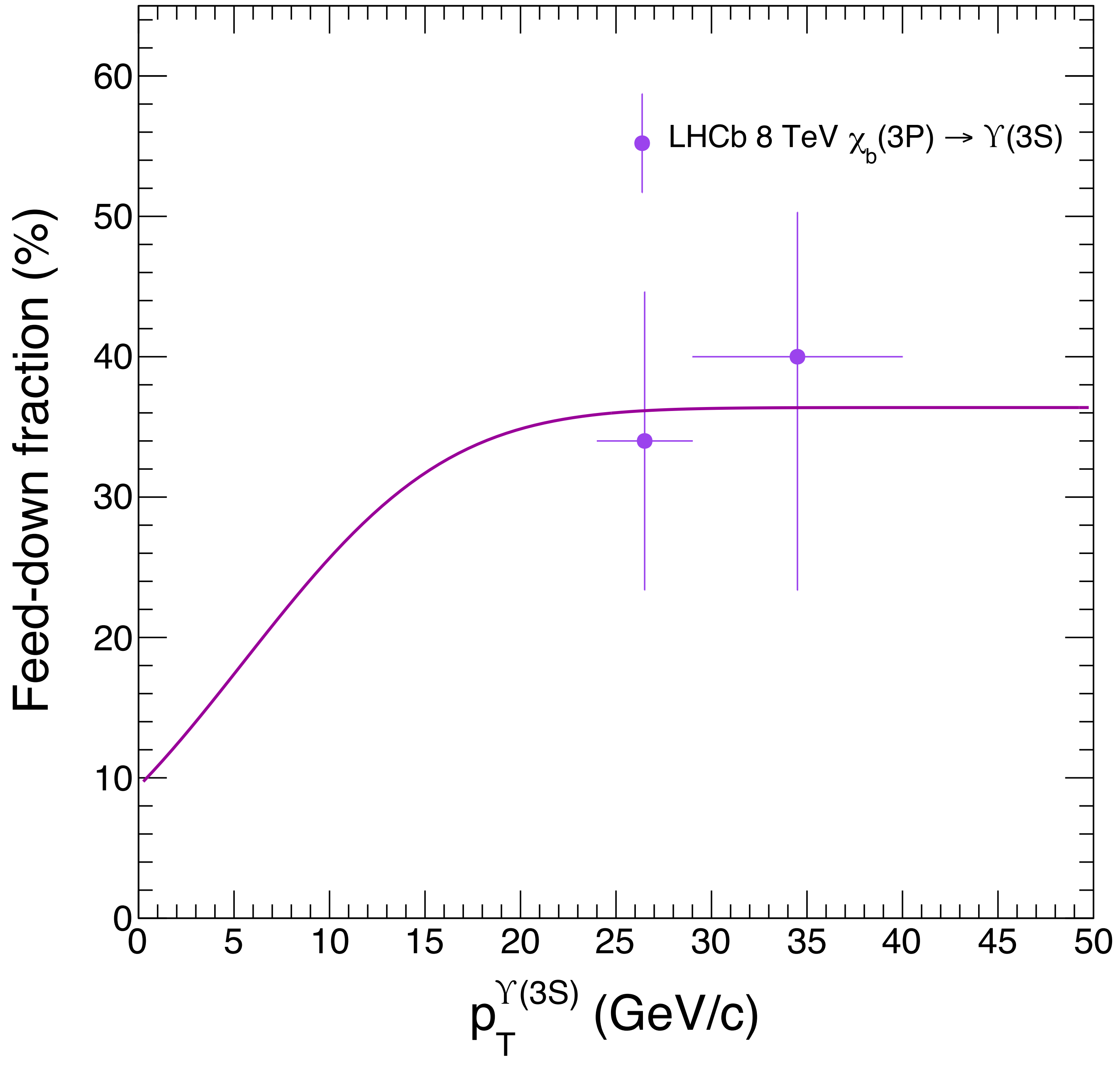
Monte Carlo simulation framework of quarkonia

- Feed-down contribution for Υ(nS): $R_n(p_T) = \Sigma R_i(p_T) F^{Q_i}_{Q_n}(p_T)$
  - R_n: weighted averaged value for Υ(nS)
  - R_i: certain state value for Υ(nS)
  - $F^{Q_i}_{Q_n}(p_T)$: feed-down fraction
  - Assumption: $R_{\Upsilon(2S)} \simeq R_{\chi(1P)}$ and $R_{\Upsilon(3S)} \simeq R_{\chi(2P)} \simeq R_{\chi(3P)}$



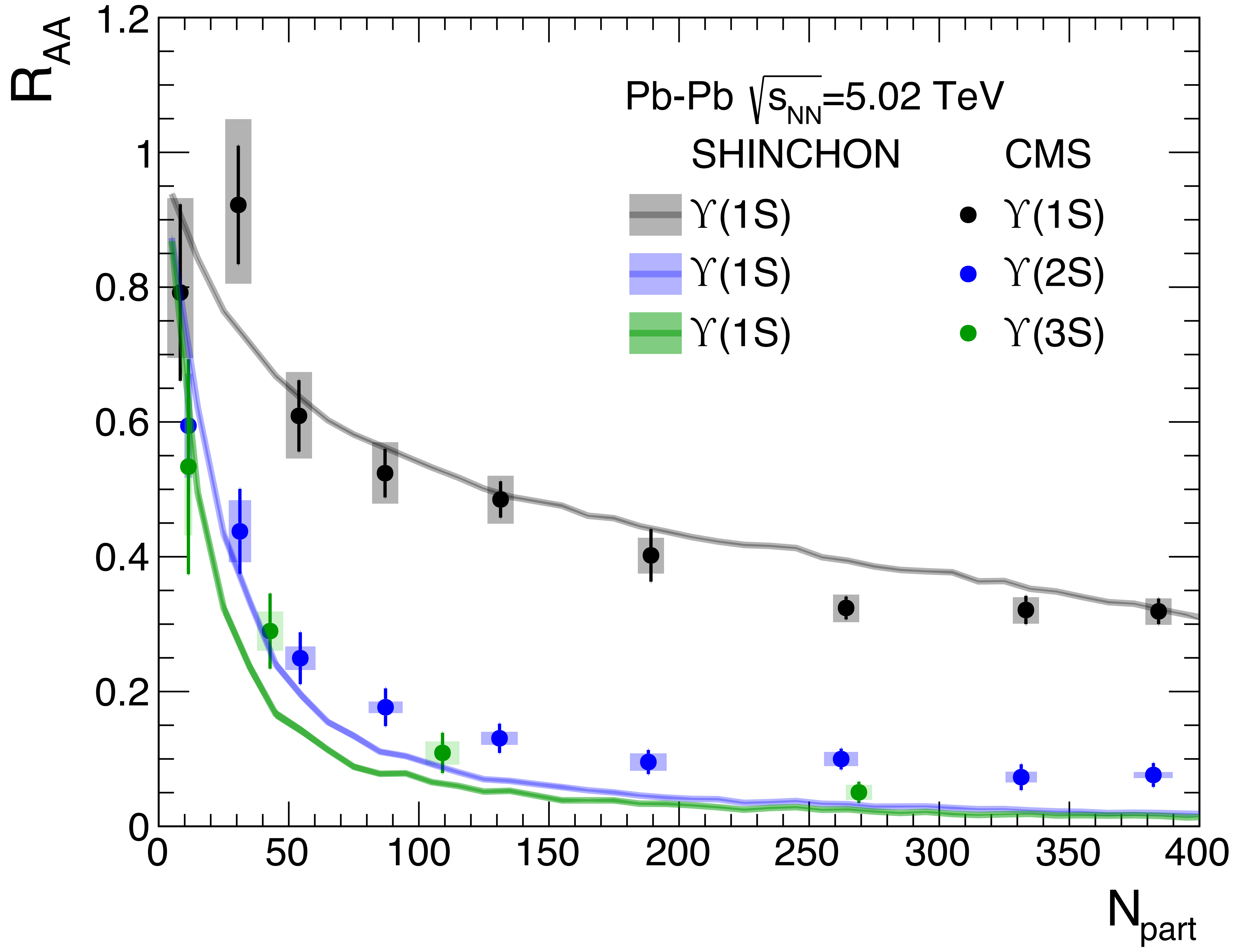


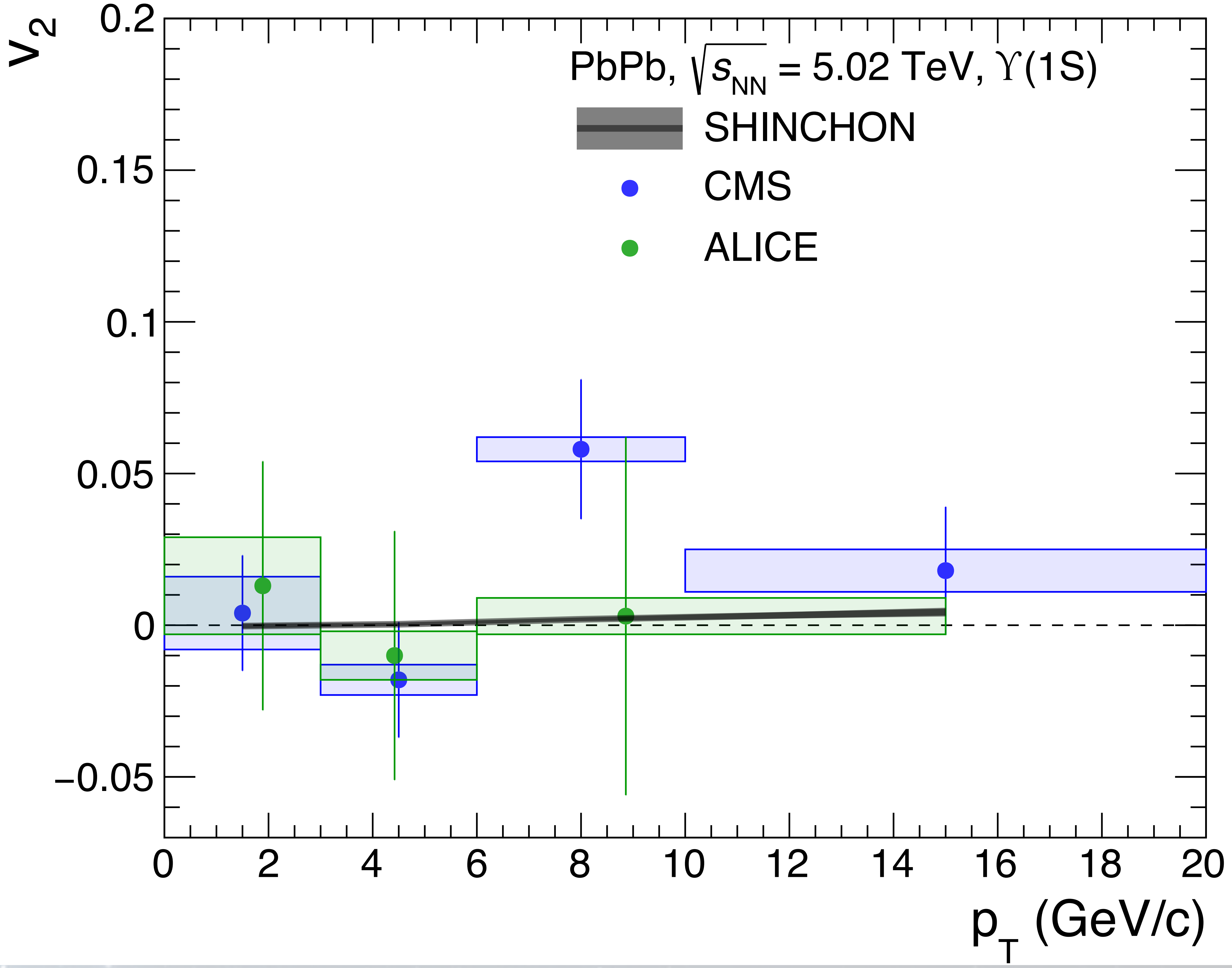




SHINCHON results in heavy-ion collisions

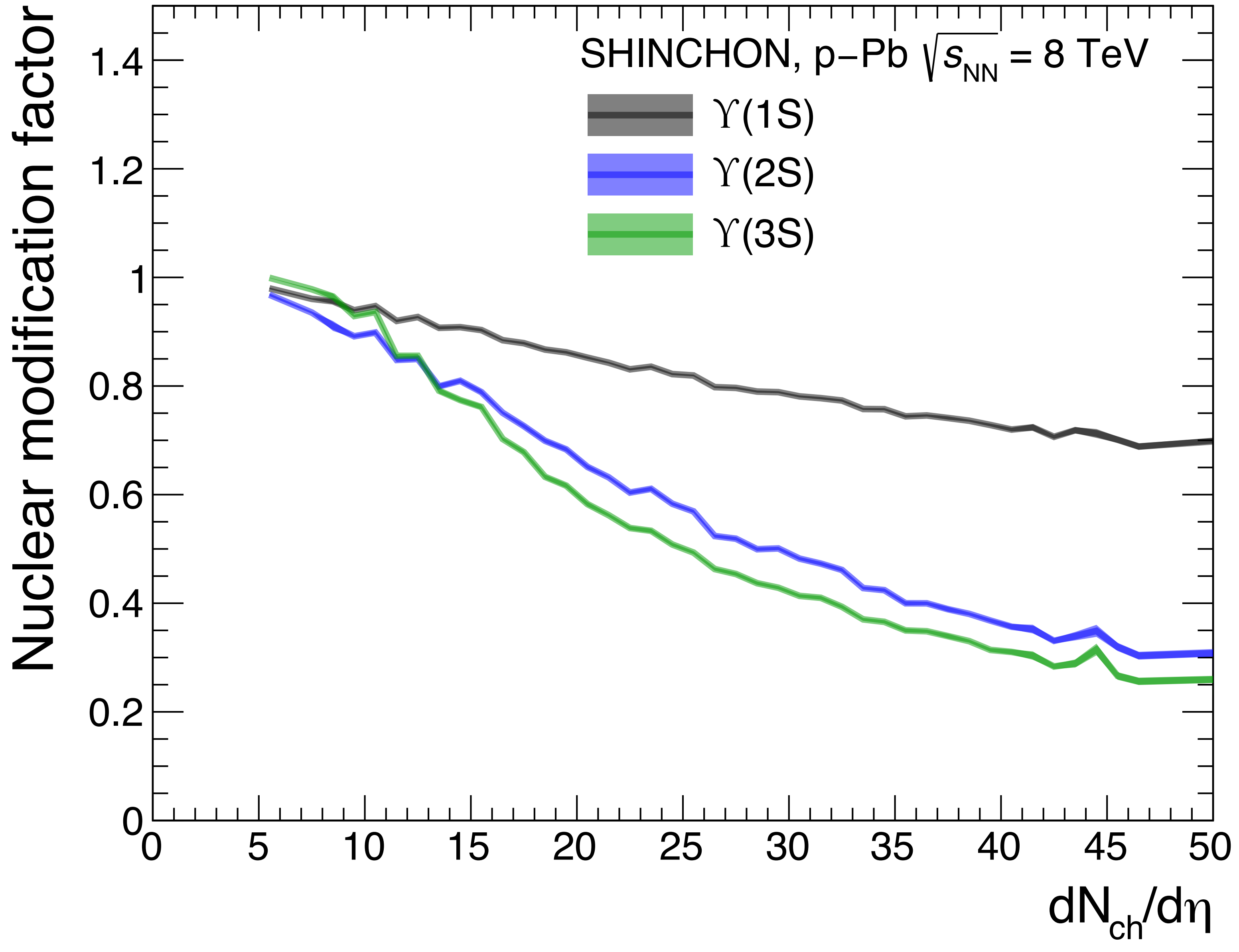
- **Framework demonstration in Pb+Pb**
  - **R_{AA}**: ϒ(1S) shows consistency with the measurement.
    - ϒ(2S) and ϒ(3S) show inconsistency in central collisions due to the exception of regeneration.
  - **V_2** of ϒ(1S): consist with measurements (≃0).

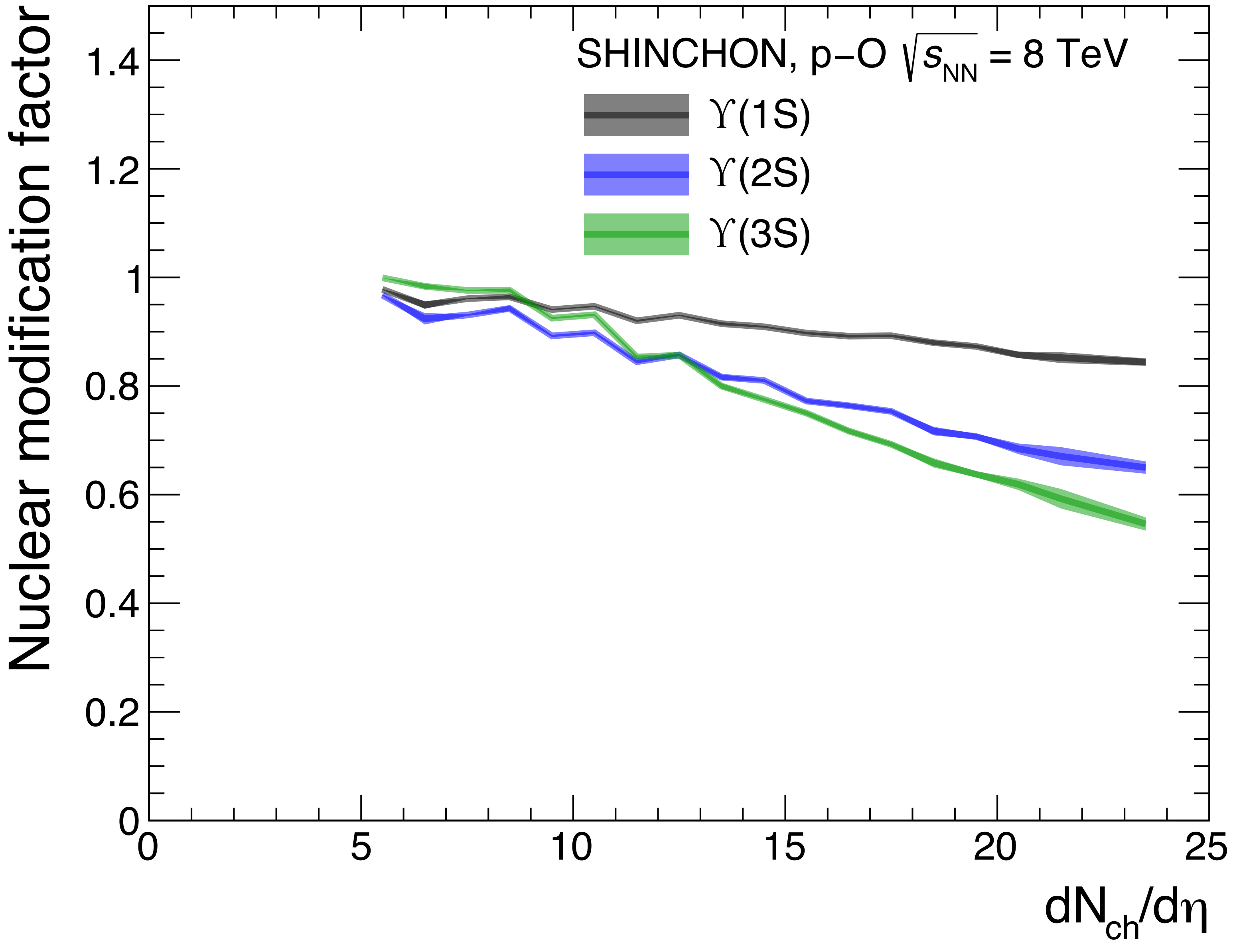


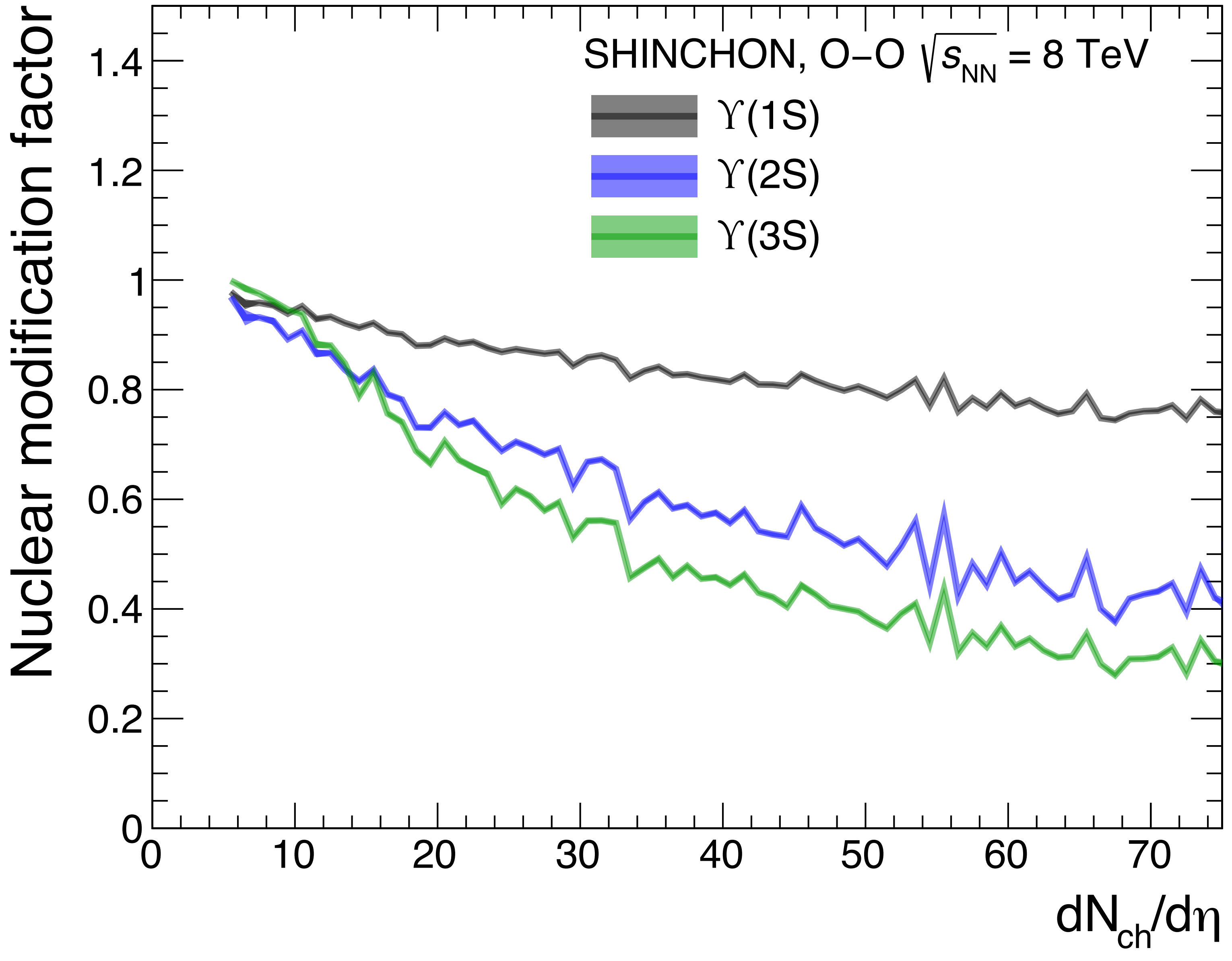


SHINCHON results in small collisions system

- **Nuclear modification factor**
  - **Gradual suppresion** with increasing event multiplicity for all three ϒ(nS) in p+Pb, p+O, and O+O
  - **Suppression**: **ϒ(1S) < ϒ(2S) < ϒ(3S)** towards higher $dN_{ch}/d\eta$
    - less suppression of ϒ(3S) in low multiplicity events: Delayed formation time

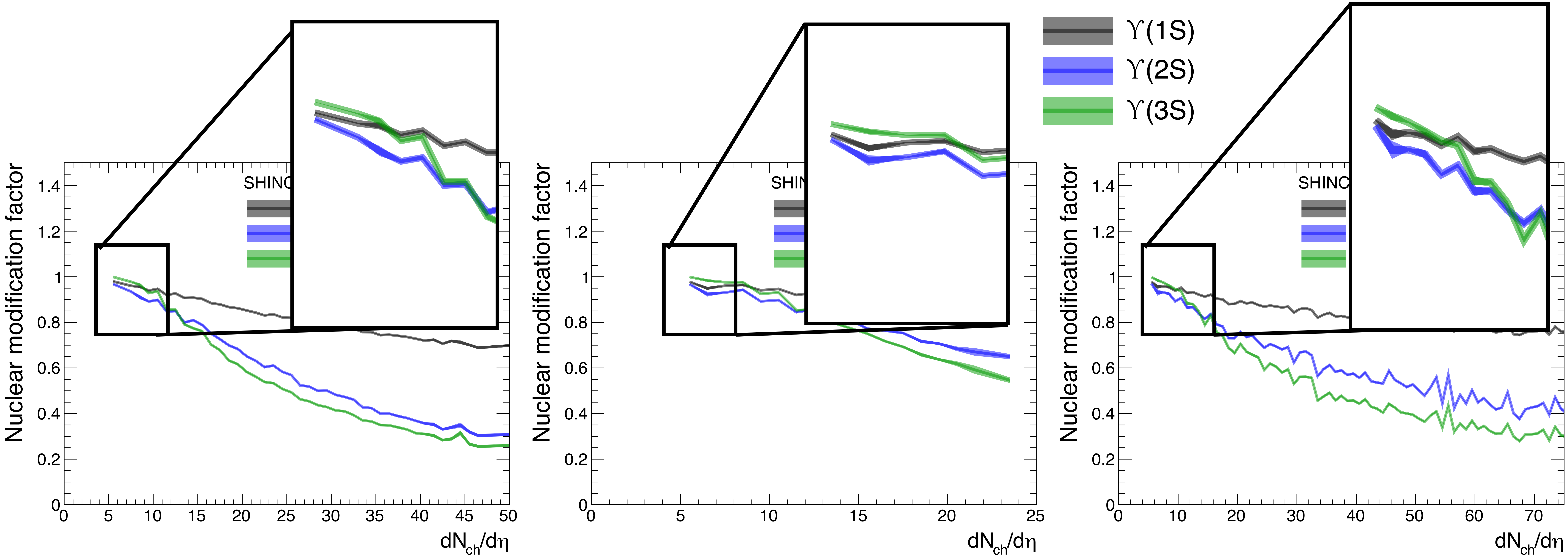






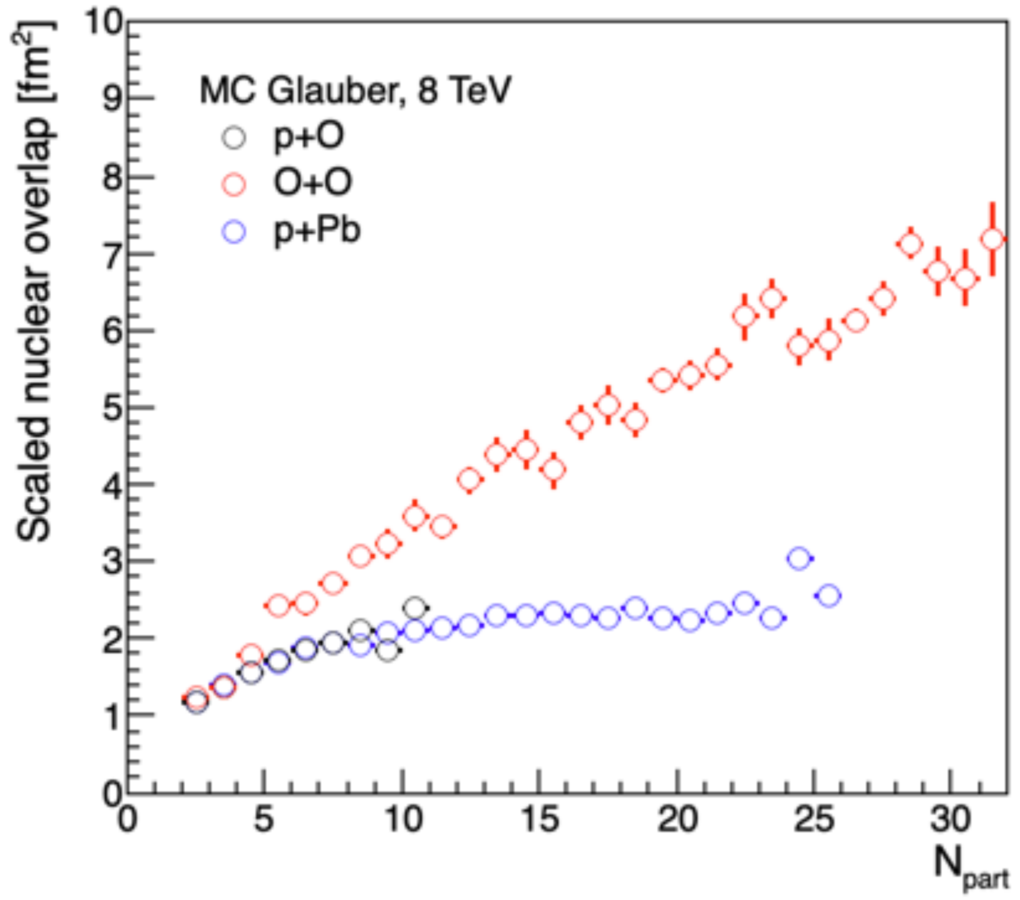
SHINCHON results in small collisions system

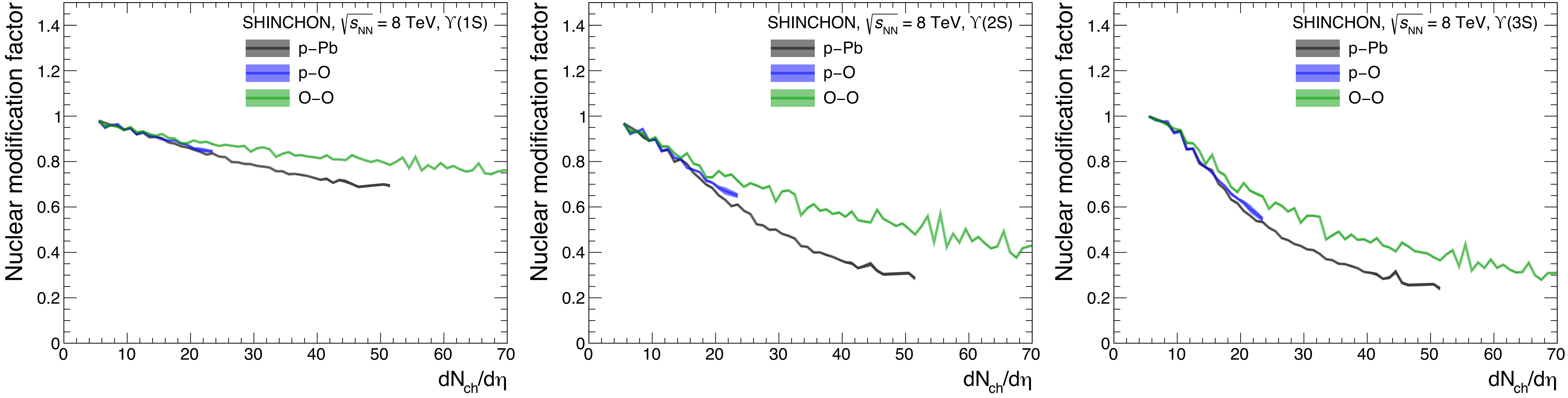
- **Nuclear modification factor**
  - **Gradual suppresion** with increasing event multiplicity for all three Υ(nS) in p+Pb, p+O, and O+O
  - **Suppression**: **Υ(1S) < Υ(2S) < Υ(3S)** towards higher $dN_{ch}/d\eta$
    - less suppression of Υ(3S) in low multiplicity events: late formation time of Υ(3S)



SHINCHON results in small collisions system

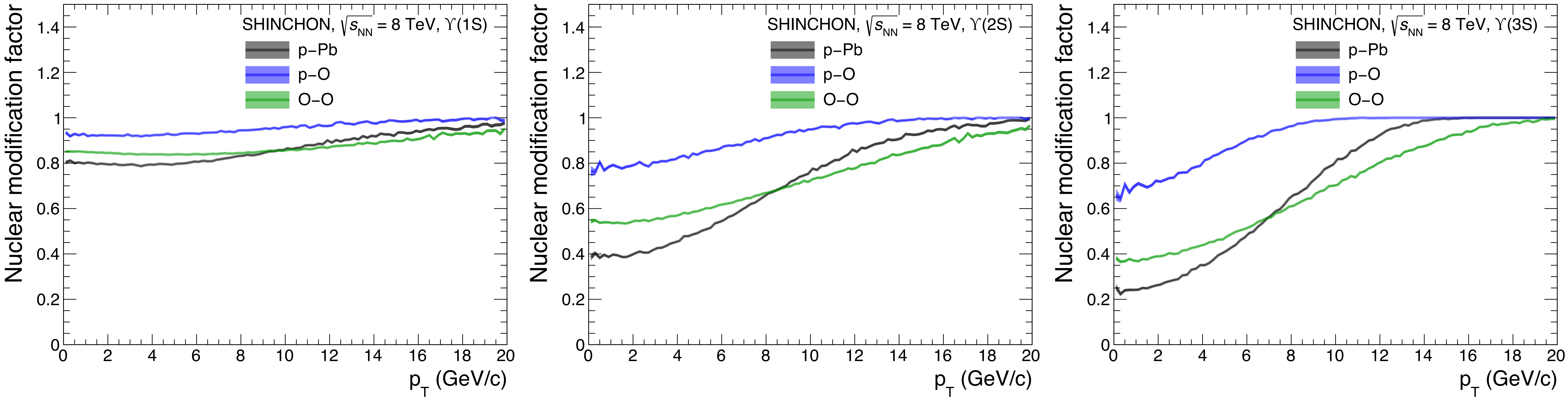
- **Nuclear modification factor**
  - **Suppression:**
    - Low multiplicity**: p+Pb ≃ p+O > O+O** ($dN_{ch}/d\eta < 25$),
    - High multiplicity**: p+Pb > O+O**
      - System size: O+O > p+Pb > p+O,   Energy density: p+Pb > O+O





SHINCHON results in small collisions system

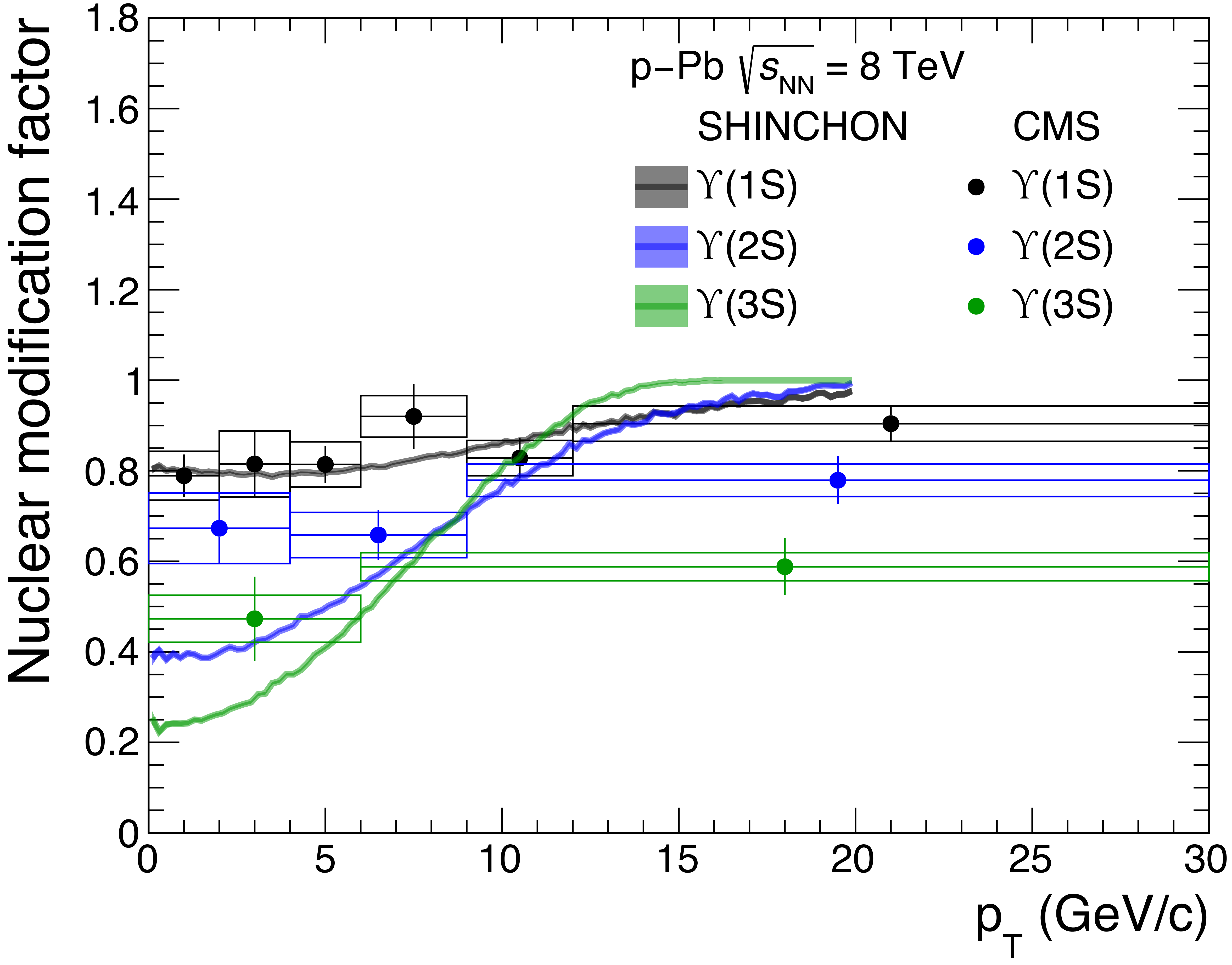
- **Nuclear modification factor**
  - At the low p_T: **$R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$**
  - At the high p_T: late formation time of $\Upsilon(3S)$
    - Effective interaction time: **p+Pb < O+O** due to the smaller initial medium size.



SHINCHON results in small collisions system

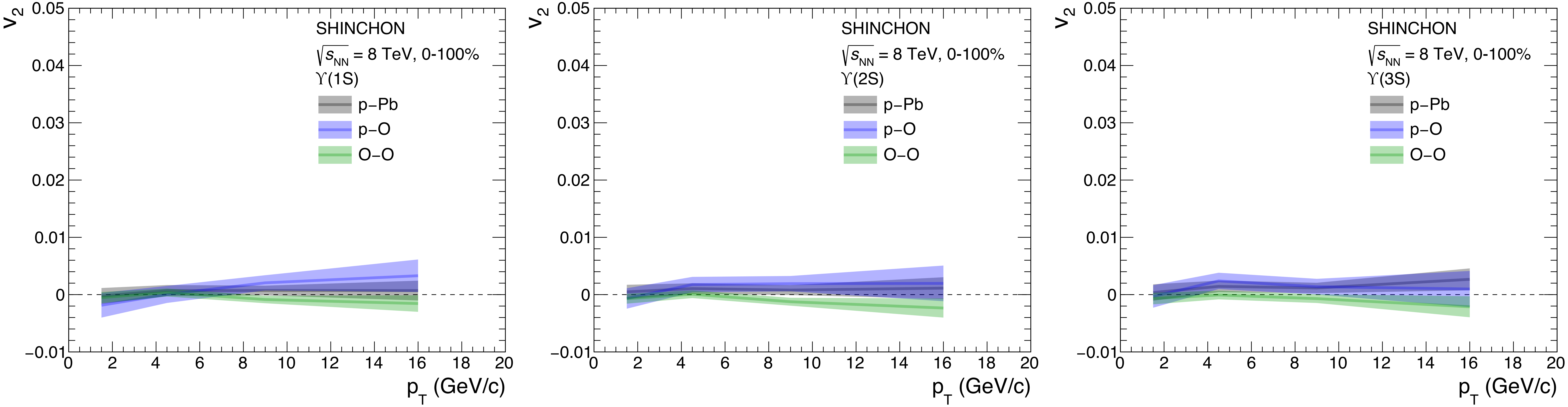
- **Nuclear modification factor**
  - **SHINCHON**: p+Pb collisions at $\sqrt{s_{NN}} = 8$ TeV
  - **CMS**: p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
    - The average multiplicity at 8TeV is about 15% higher than that at 5.02 TeV

  - **Good agreement with data for ϒ(1S)**
  - **Deviations for ϒ(2S) and ϒ(3S)**
    - **Higher multiplicity** can affect the modification of ϒ at the low p_T region.
    - **Extending the ϒ formation time** towards higher p_T induces a rapid increase of R_{pA}.



SHINCHON results in small collisions system

- **Elliptic flow**
  - **$v_2 < 0.01$** in the overall p_T region and very similar among the p+Pb, p+O and O+O.
  - The weak p_T dependence indicates that v_2 is not affected by the elongation of the formation time.



SHINCHON results in small collisions system

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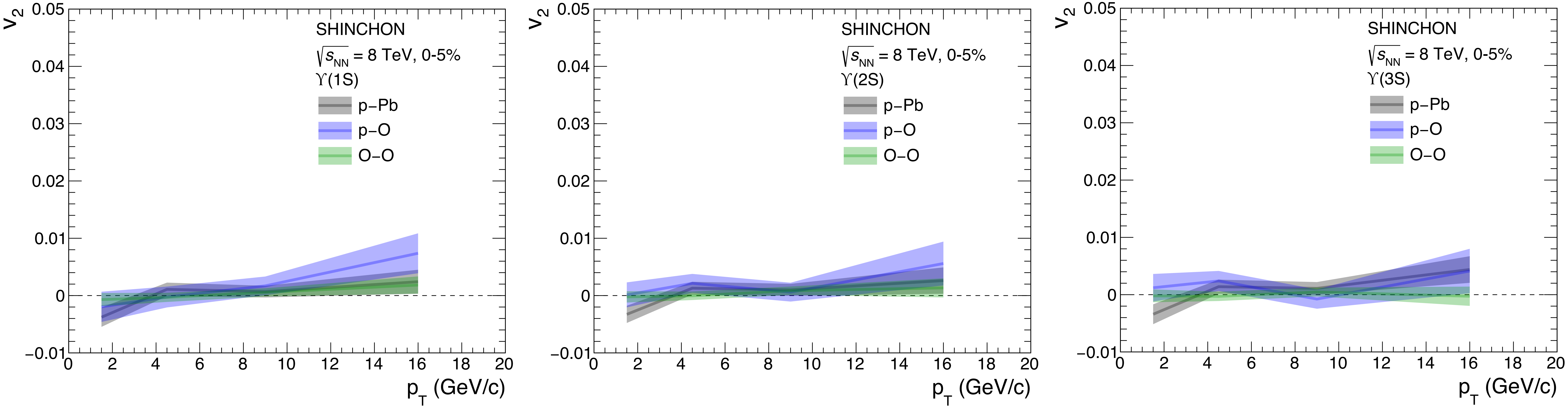
  - **$v_2 < 0.01$** in the overall p_T region and very similar among the p+Pb, p+O and O+O.
  - The weak p_T dependence indicates that v_2 is not affected by the elongation of the formation time.
  - **v_2 in high-multiplicity events > v_2 in MB events** (very slightly high)
    - In higher multiplicity events, the low p_T Υ(nS) traverses very slowly.

      ➡ Not escape the medium before the chemical freeze-out temperature.



Summary

- **SHINCHON** has been developed based on the theoretical calculation of the thermal with of Υ(nS) and the publicly available codes to describe the initial condition and evolution of heavy-ion collisions.
- **$R_{pA,AA}$(Υ(1S)) > $R_{pA,AA}$(Υ(2S)) > $R_{pA,AA}$(Υ(3S))**
  - less suppression of Υ(3S) in low multiplicity events
    - Due to the late formation time of Υ(3S)
  - Modification in high multiplicity: O+O < p+Pb
    - Due to the energy density
- **V_2 of Υ(nS) < 0.01** for all three systems, even in high multiplicity events.

- **SHINCHON** can provide valuable information on sources of nuclear effects on bottomonia production in small systems upcoming LHC Run.

Paper in preparation

Model study on $\Upsilon(nS)$ modification in small collision systems

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(Dated: August 30, 2022)

Heavy quarkonia production has been studied extensively in relativistic heavy-ion collision experiments to understand the properties of the Quark-Gluon Plasma. Experimental results on the yield modification in heavy-ion collisions relative to p+p collisions can be described by several models considering dissociation and regeneration effects. A yield modification beyond initial-state effects has also been observed in small collision systems such as p+Au and p+Pb collisions. Still, it is not yet concluded that there is a hot medium effect. A model study in various small collision systems such as p+p, p+Pb, p+O, and O+O collisions will help quantitatively understand nuclear effects on the $\Upsilon(nS)$ production. A theoretical calculation considering the gluo-dissociation and inelastic parton scattering and their inverse reaction reasonably describe the suppression of $\Upsilon(1S)$ in Pb+Pb collisions. Based on this calculation, a Monte Carlo simulation is developed to more realistically incorporate the medium produced in heavy-ion collisions with event-by-event initial collision geometry and hydrodynamic evolution. We extend this framework to small systems to study the medium effects. In this work, we quantify the nuclear modification factor of $\Upsilon(nS)$ as a function of charged particle multiplicity ($dN_{ch}/d\eta$) and transverse momentum. We also calculate the elliptic flow of $\Upsilon(nS)$ in small collision systems.

I. INTRODUCTION

Quarkonia have been long considered as golden probes to study the strongly interacting matter consisting of deconfined quarks and gluons, the quark-gluon plasma (QGP), produced in high-energy heavy-ion collisions [1–5]. Quarkonium states are produced at the early stages of the collision via hard parton scatterings, thus experiencing the full space-time evolution of the medium. Also, their spectral functions are modified due to color screening [4, 5] and interactions with medium constituents such as gluo-dissociation or landau damping [6–8]. Consequently, the quarkonium yields are expected to be suppressed in heavy ion collisions with respect to expectations from proton-proton (p+p) data, following the order of their binding energies. On the other hand, the yields of quarkonia can be enhanced in the presence of the QGP by recombination processes of uncorrelated as well as correlated quarks [9–12].

The modification of the quarkonium yields have been studied by various experiments at RHIC and LHC using the nuclear modification factor quantified as the yield ratio in nucleus-nucleus collisions (A+A) to that in p+p collisions [13–20]. One of the most remarkable signatures is the ordered suppression of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons by their binding energies reported in LHC [16, 18–20].

To better understand the in-medium effects of quarkonia in A+A collisions in a sophisticated way, it is important to study the "cold nuclear matter" (CNM) effects which are typically probed using proton-nucleus (p+A) collisions. Modification of parton distribution functions in the nucleus [21], energy loss [22] or nucleus absorption [23, 24], and interactions with comoving particles [25–27] are examples of CNM effects. On the other hand, various experiment collaborations have reported capital results, suggesting a QGP-like behavior of the created medium also in smaller collision systems, such as the observation of long-range collective azimuthal correlations in high multiplicity regions [28–38]. Therefore, sophisticated phenomenological studies in such interactions become the subject that is sensitive to understanding the quarkonium production in small collision systems.

In this paper, we report a detailed study of the in-medium effects for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons in proton-lead (p+Pb), proton-oxygen (p+O), and oxygen-oxygen (O+O) collisions. Theoretical calculations for dissociation of $\Upsilon(nS)$ [39] are incorporated with the SONIC framework [40] to describe the time evolution of the medium. The dissociation component is constraint in potential non-relativistic QCD (pNRQCD) limits, and coupled into the Boltzmann equation. The thermal width is calculated based on hard thermal loop (HTL) perturbation theory using the Bethe-Salpeter amplitude, while the recombination part is treated as the inverse reactions of gluo-dissociation and inelastic parton scattering. We report the nuclear modification factors and the second-order Fourier coefficient (v_2) of the azimuthal distribution of $\Upsilon(nS)$ mesons in p+Pb, p+O, and O+O collisions. For the demonstration of the framework, we also present the results in Pb+Pb collisions and compare them with the experimental results.

BACK UP

SHINCHON results in small collisions system

- System size: O+O > p+Pb > p+O,
- Energy density: p+Pb ≈ p+O > O+O