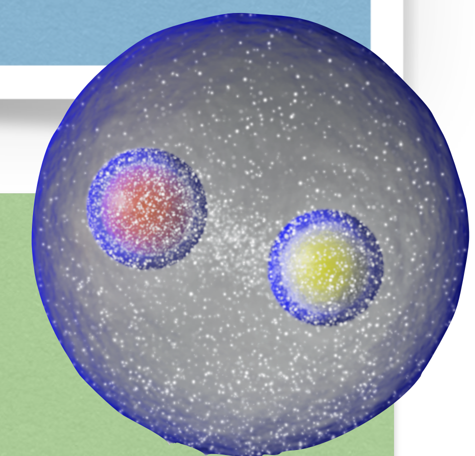
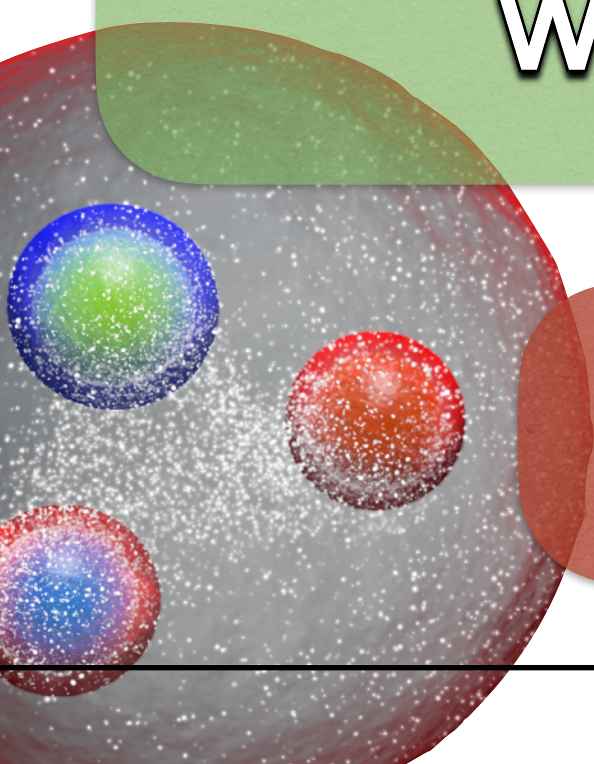
Model study on Upsilon modification in small systems



SHINCHON

Simulation for Heavy IoN Collision with Heavy-quark and ONia



JaeBeom Park (Korea University)

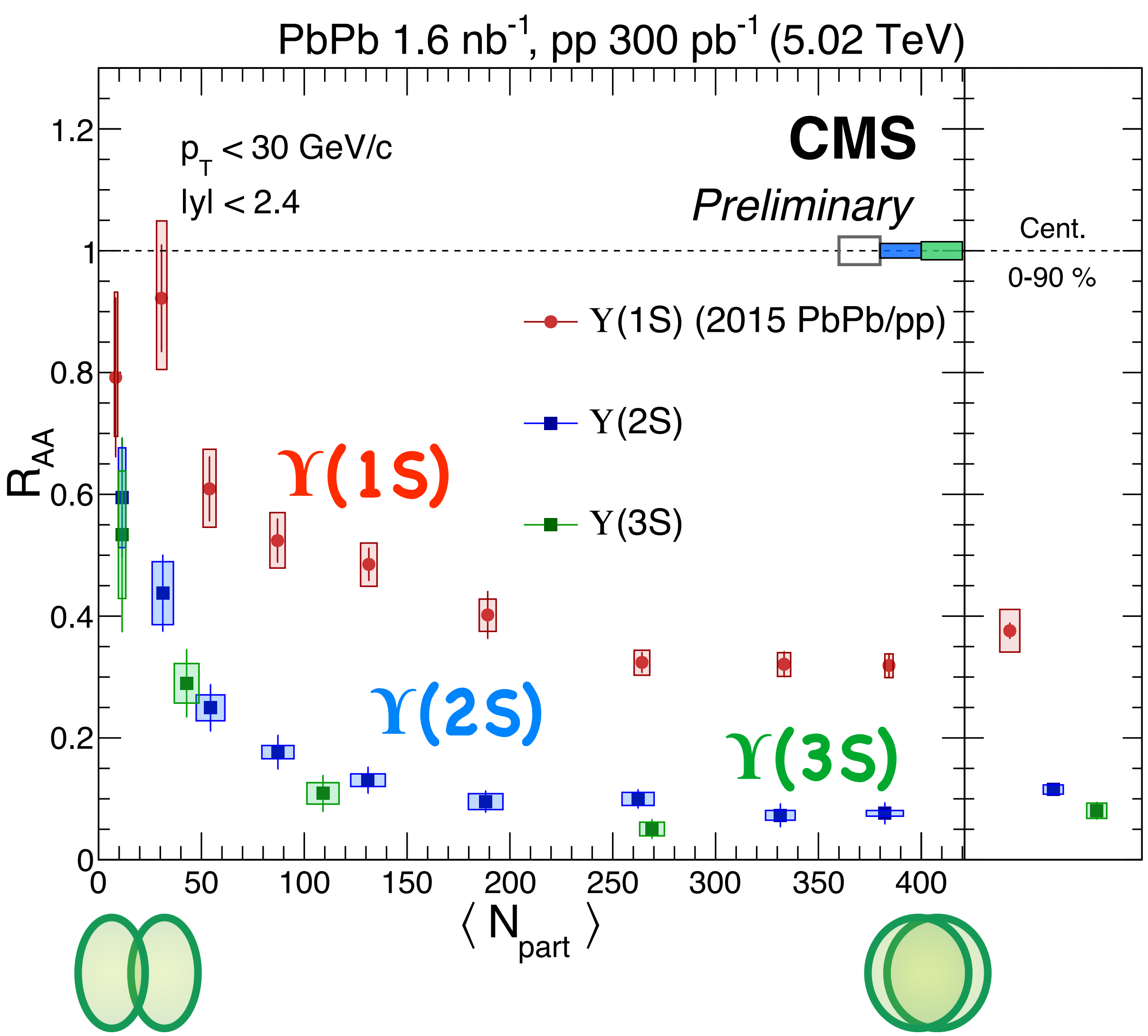
Junlee Kim, Jinjoo Seo, Byungsik Hong, Juhee Hong, Eun-Joo Kim, Yongsun Kim, MinJung Kweon, Su Houng Lee, Sanghoon Lim

What have we learned so far for Upsilon modification in heavy-ion collisions?

What have we learned so far for Upsilon modification in heavy-ion collisions?

From data

☑ Sequential suppression in AA @ LHC!!



- Amount of suppression :

  Y(1S) < Y(2S) < Y(3S)

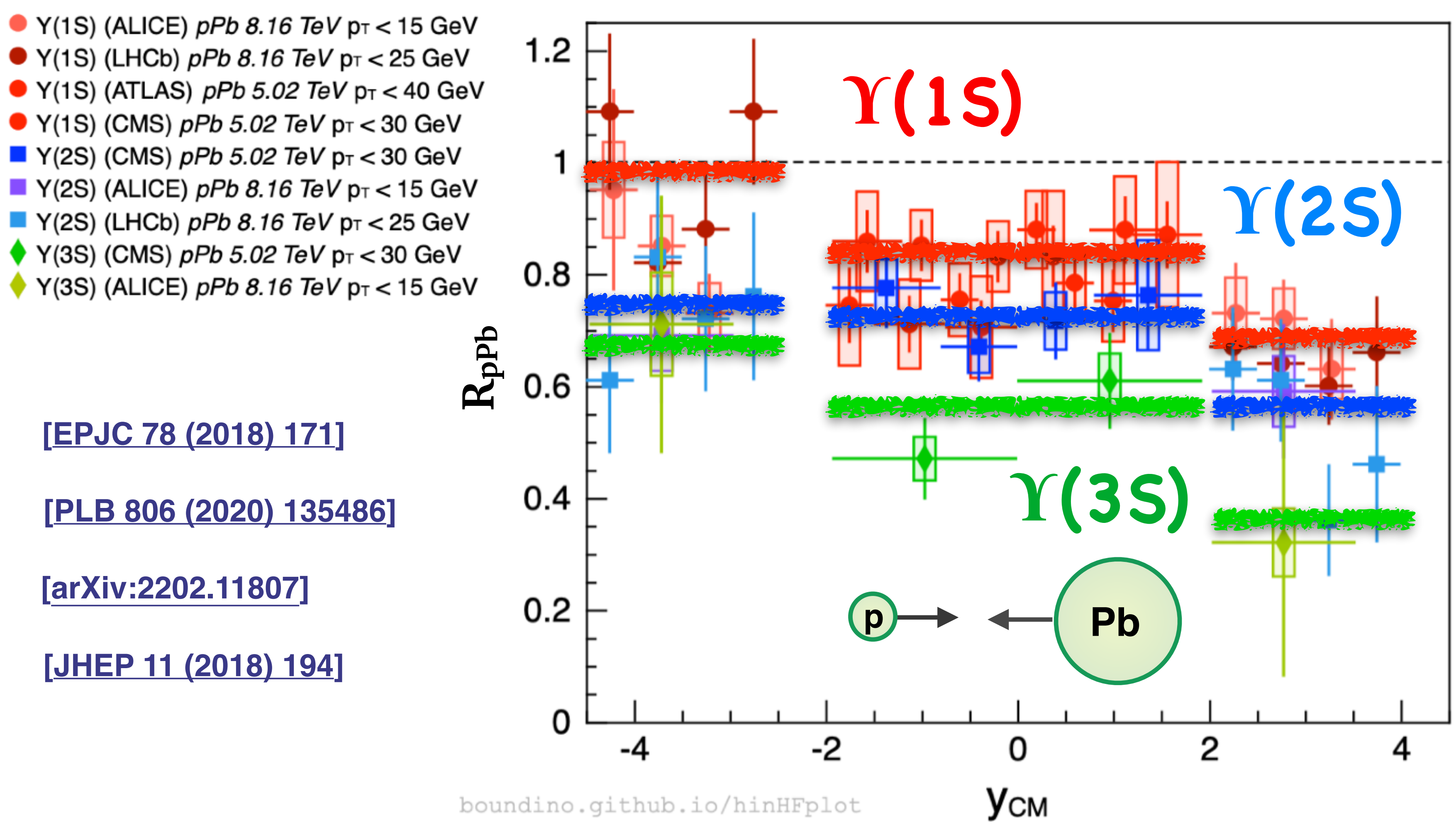
- Binding energy :

  Y(1S) > Y(2S) > Y(3S)

What have we learned so far for Upsilon modification in heavy-ion collisions?

From data

- ☑ Sequential suppression in AA @ LHC!!
- ☑ Sequential suppression in pA @ LHC!!



[EPJC 78 (2018) 171]

[PLB 806 (2020) 135486]

[arXiv:2202.11807]

[JHEP 11 (2018) 194]

- Amount of suppression :

  Υ(1S) < Υ(2S) < Υ(3S)

  absolute suppression smaller than PbPb

- Binding energy :

  Υ(1S) > Υ(2S) > Υ(3S)

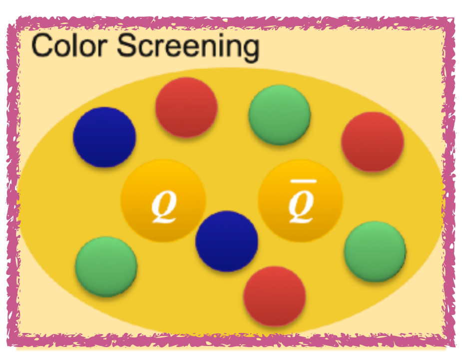
What have we learned so far for Upsilon modification in heavy-ion collisions?

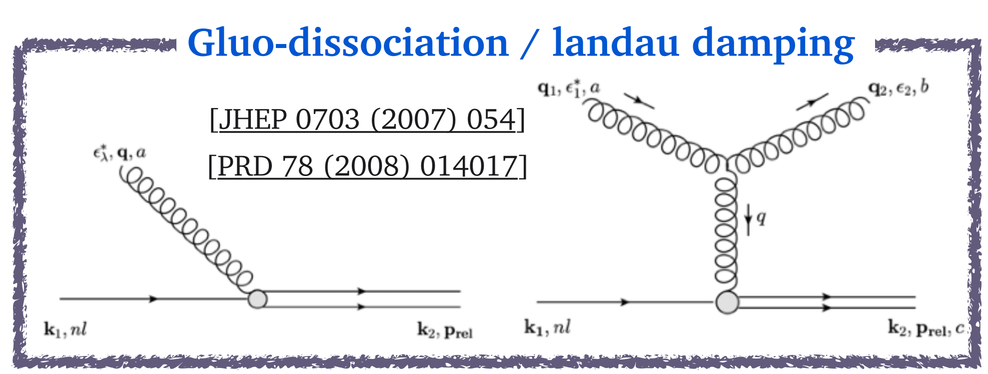
From data

- ☑ Sequential suppression in AA @ LHC!!
- ☑ Sequential suppression in pA @ LHC!!

From theory

- ☑ Calculations for dissociation processes —> Suppression
  — static/dynamical screening captured as real/impaginary part of the potential





What have we learned so far for Upsilon modification in heavy-ion collisions?

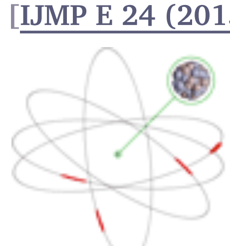
From data

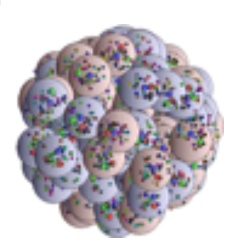
- ☑ Sequential suppression in AA @ LHC!!
- ☑ Sequential suppression in pA @ LHC!!

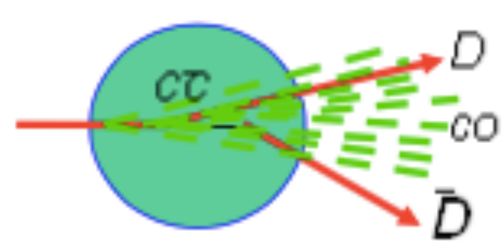
From theory

- ☑ Calculations for dissociation processes —> Suppression
  — static/dynamical screening captured as real/impaginary part of the potential
- ☑ Recombination process —> Enhancement
  — correlated/uncorrelated recombination or off-diagonal/diagonal components
- ☑ Initial/Final state effect apart from hot-medium effects
  — nPDF, CGC, coherent energy loss, comover breakup, etc.

[IJMP E 24 (2015) 1530008]

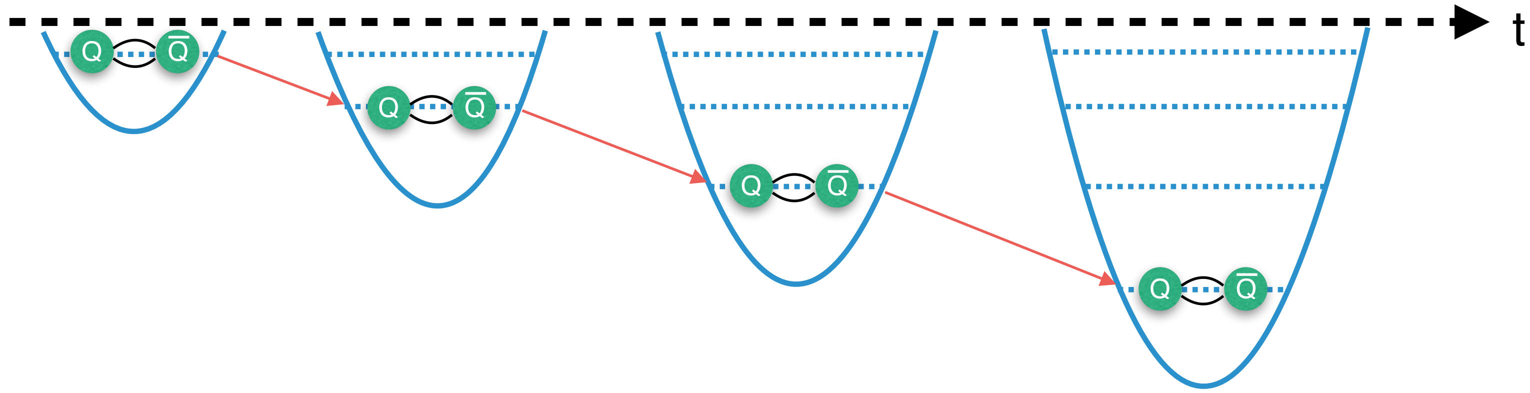




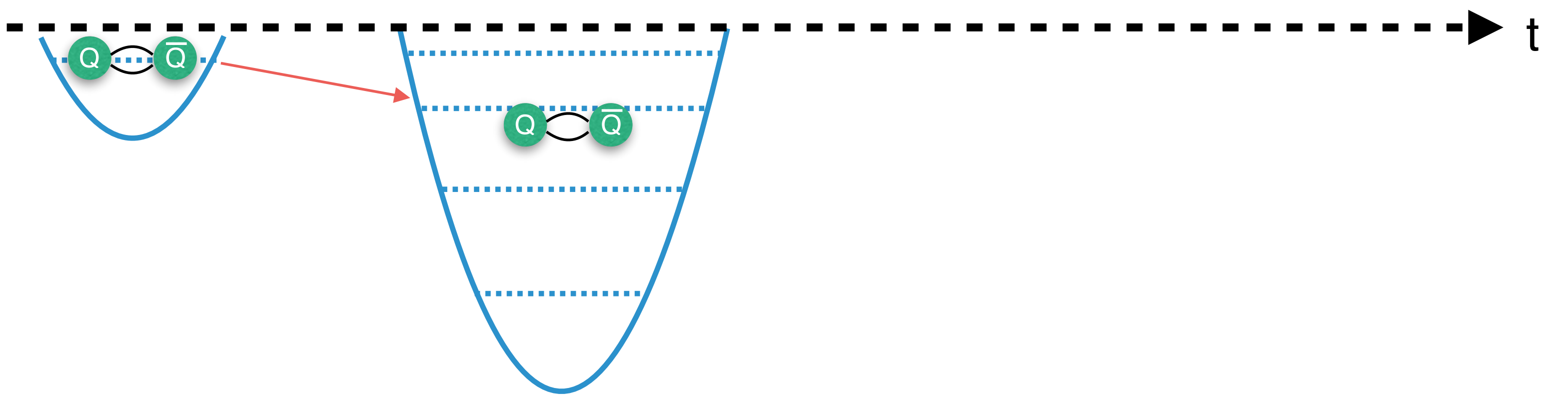


Quarkonium state in medium

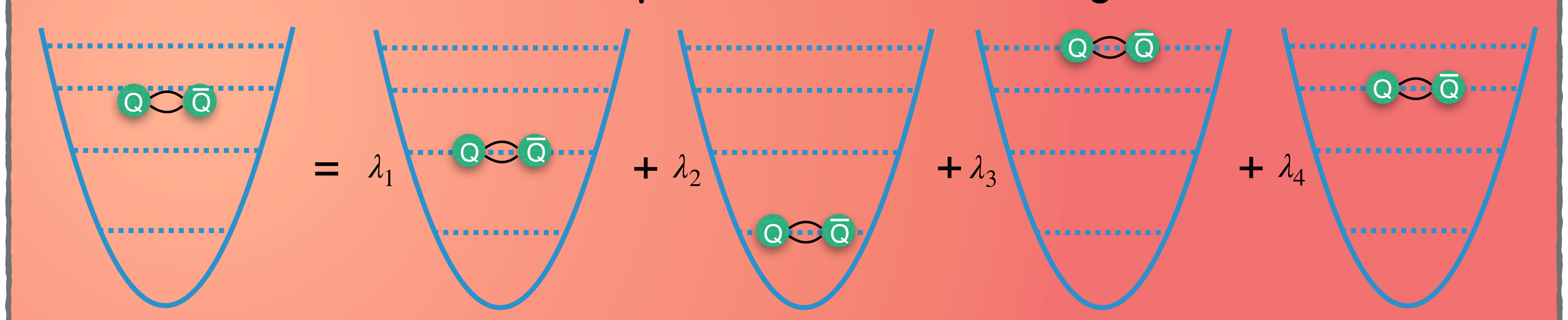
If the medium evolves slowly : state remains in a given eigenstate



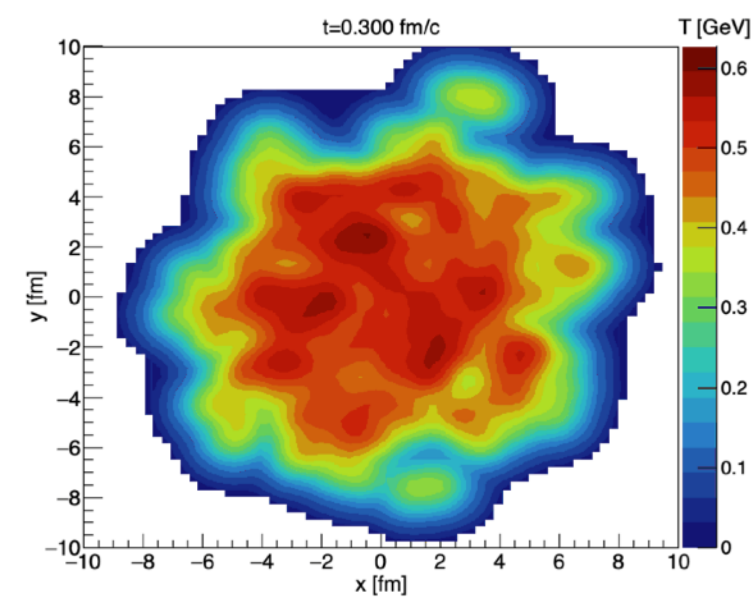
In reality : rapid expansion —> too fast to catch the change of the potential



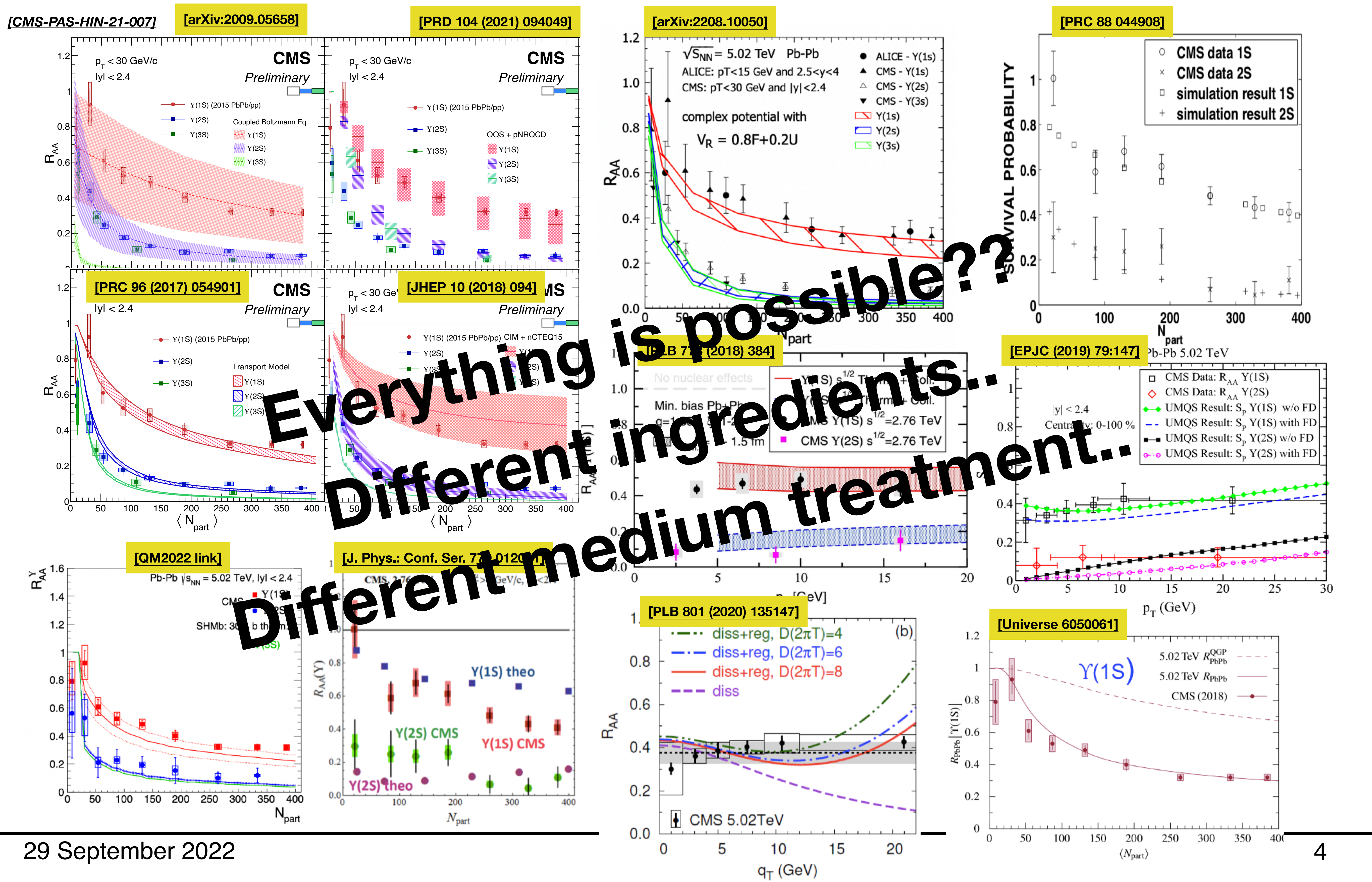
Q-Qbar state = projection on various eigenstates



- Rapid expansion…
- Corona region..
- Hydrodynamics…
- …



Theory vs data comparison



Everything is possible??

Different ingredients..

Different medium treatment..

SHINCHON

Simulation for Heavy IoN Collision with Heavy-quark and ONia

arXiv:2209.12303v1 [nucl-th] 25 Sep 2022

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

Junlee Kim,[3] Jinjoo Seo,[1] Byungsik Hong,[6] Juhee Hong,[2] Eun-Joo Kim,[3] Yongsun Kim,[5] MinJung Kweon,[1] Su Houng Lee,[2] Sanghoon Lim,[4] and Jaebeom Park[6]

[1] *Department of Physics, Inha University, Incheon 22212, South Korea*
[2] *Department of Physics and Institute of Physics and Applied Physics, Yonsei University, Seoul 03722, Korea*
[3] *Division of Science Education, Jeonbuk National University, Jeonju 54896, South Korea*
[4] *Department of Physics, Pusan National University, Busan, 46241, South Korea*
[5] *Department of Physics, Sejong University, Seoul, 05006, South Korea*
[6] *Department of Physics, Korea University, Seoul 02841, South Korea*

(Dated: September 27, 2022)

Quarkonium production has been studied extensively in relativistic heavy-ion collision experiments to understand the properties of the quark gluon plasma. The experimental results on the yield modification in heavy-ion collisions relative to that in $p+p$ 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, but it is still premature to claim any 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 understanding 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 long been 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 scaled by the average number of binary NN 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 experiments 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. 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, and the contribution of feed-down from higher excited states are considered to compare with the experimental data properly. For the demonstration of the framework, we also present the results in Pb+Pb colli-

- **Performance studies on theory models in the same simulation framework**
- **How much would the yields be modified w.r.t the potential parameterization under the same medium evolution condition? (and vice versa)**
- **Test the sensitivity of different models & simulation frameworks for the response of quarkonia-in-media**

Today : Application Υ modification in small systems (pO, OO, pPb)

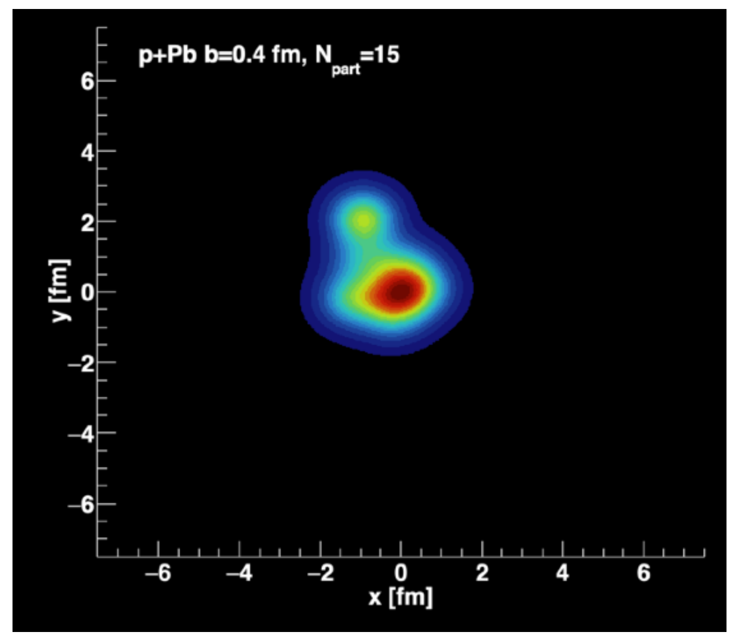
Framework setup

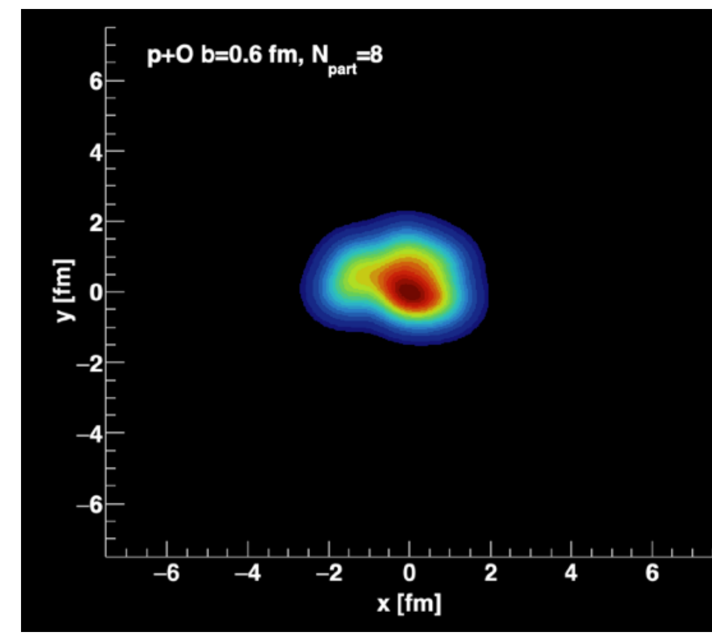
PRC 99, 034905 (2019)

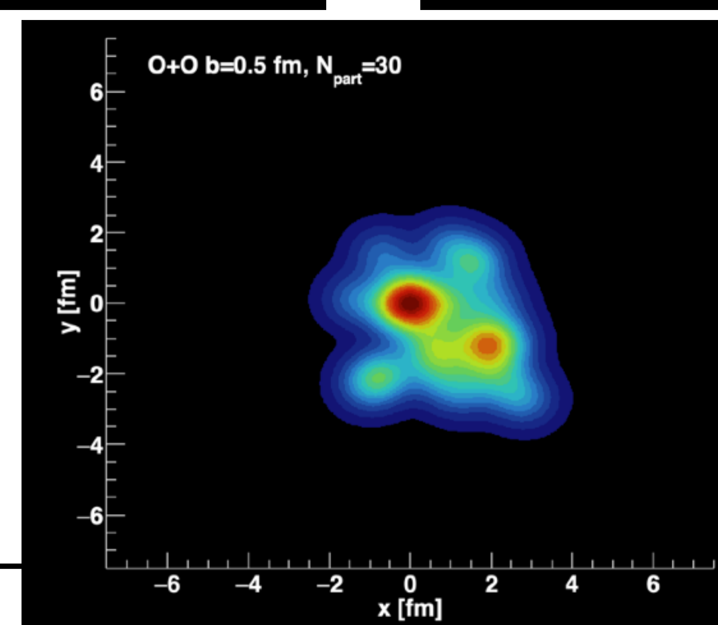
MC Glauber
+
SONIC

Geometry generation
+
Hydrodynamics

- 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







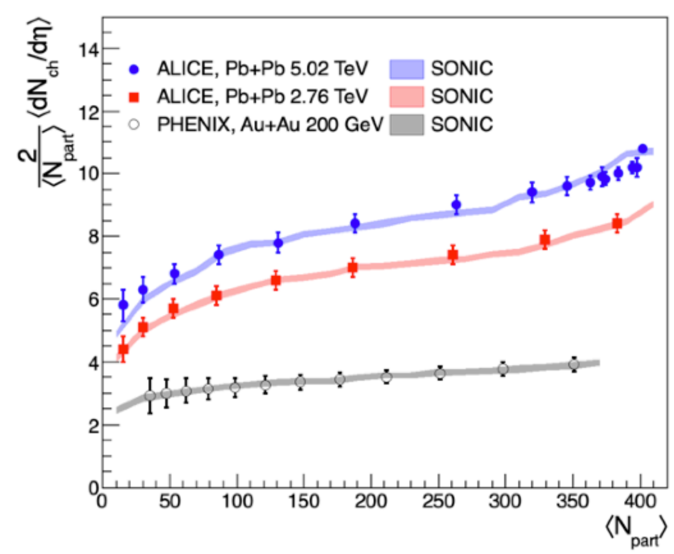
Framework setup

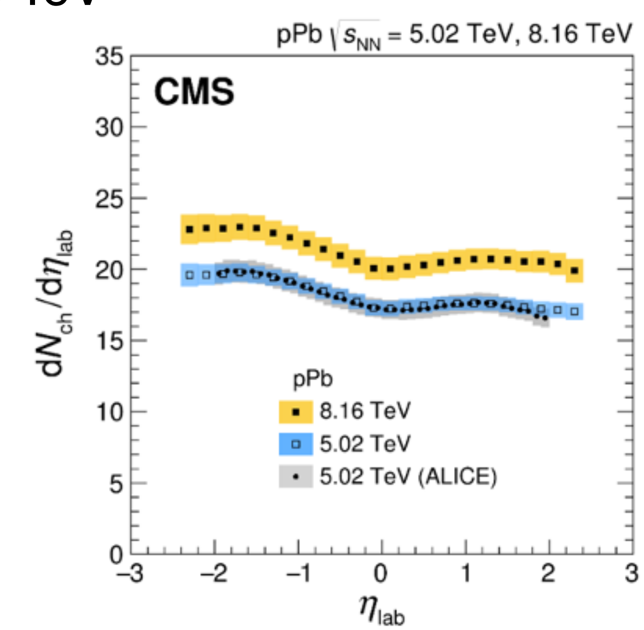
PRC 99, 034905 (2019)

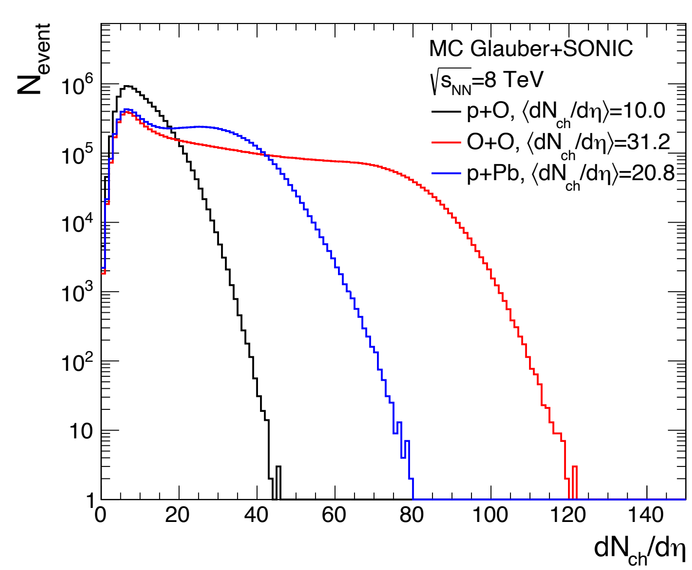
MC Glauber
+
SONIC

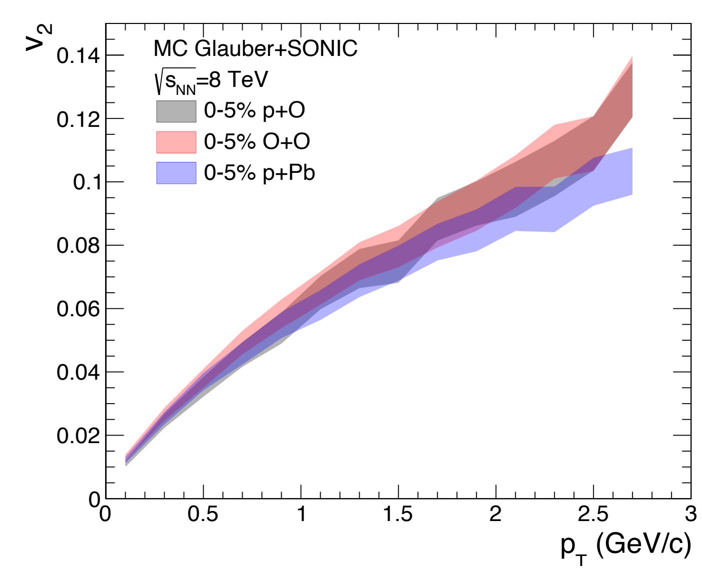
Geometry generation
+
Hydrodynamics

- Hydrodynamic simulation: **SONIC** framework
  - η/s = 0.08 & ζ/s = 0
- Scaling MC Glauber —> Energy density for SONIC based on measured multiplicity in pPb 8.16 TeV



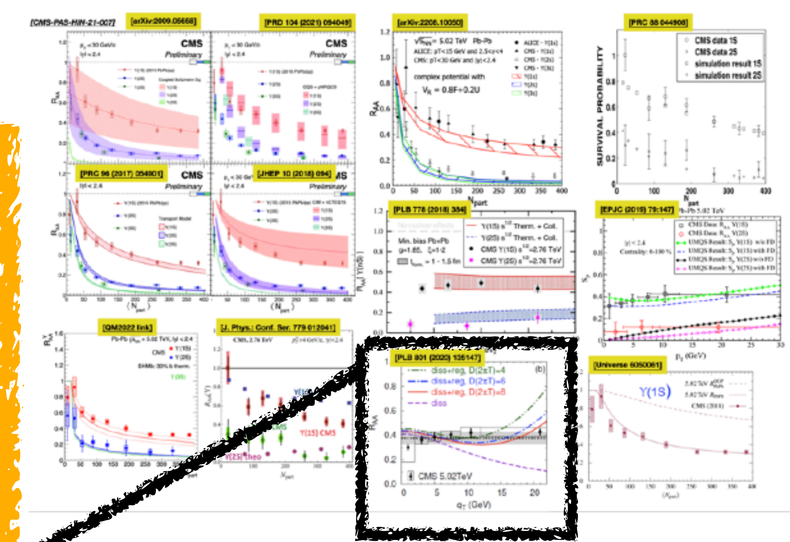






Framework setup

PRC 99, 034905 (2019)   PLB 801 (2020) 135147



MC Glauber
+
SONIC

Geometry generation
+
Hydrodynamics

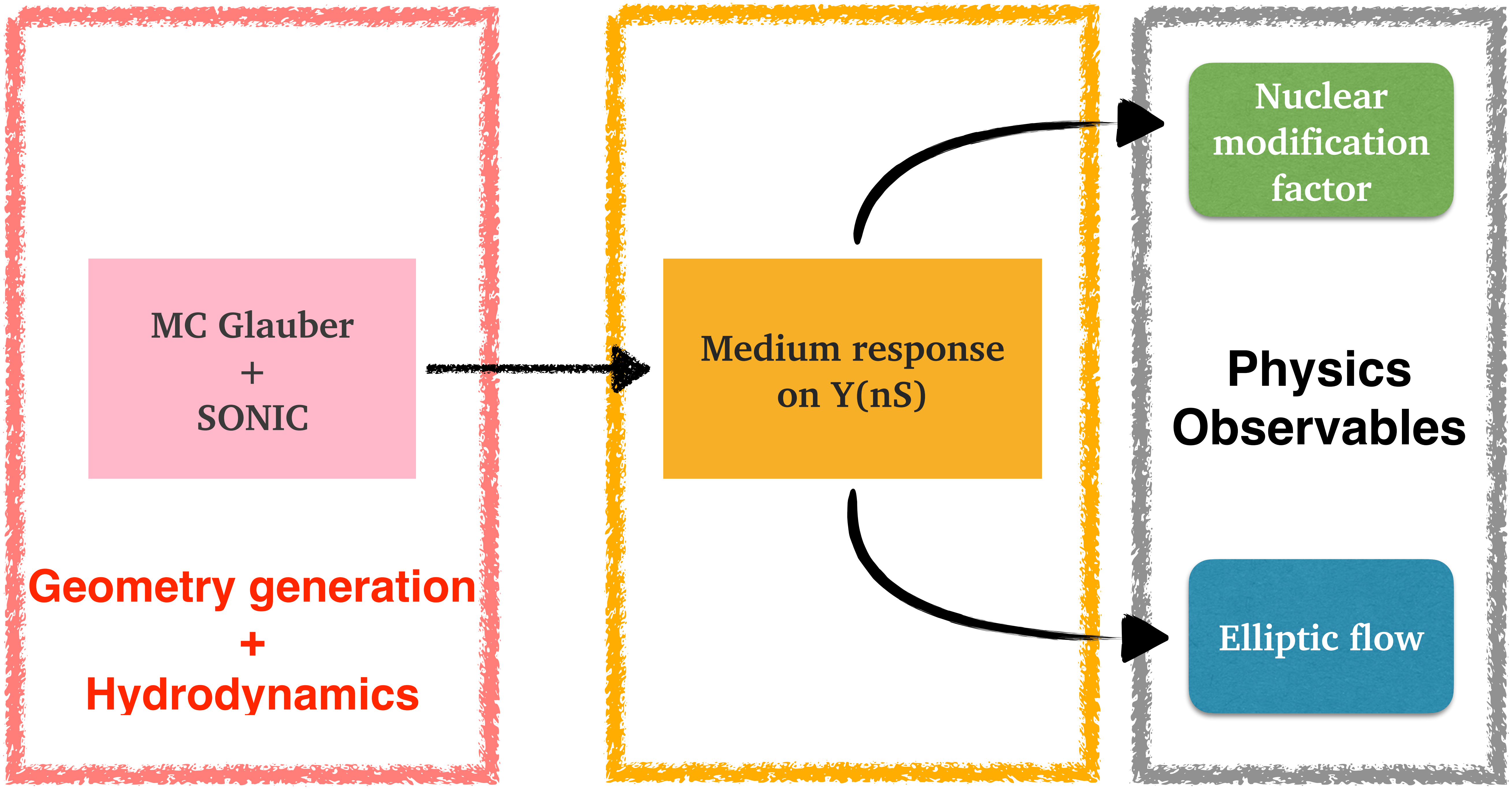
→

Medium response on Υ(nS)

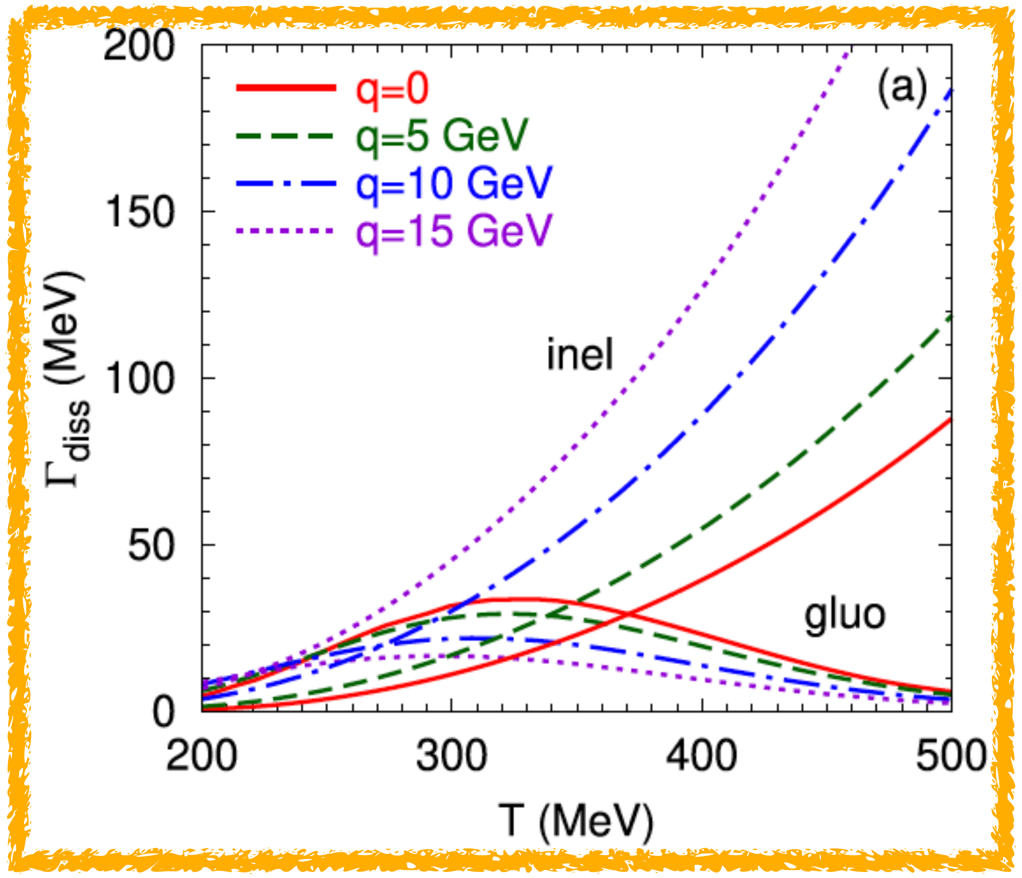
- Pickup and collaborate with a theory group that describe the Υ R_{AA} in PbPb
- Neglect recombination processes for small systems

Framework setup

PRC 99, 034905 (2019)   PLB 801 (2020) 135147



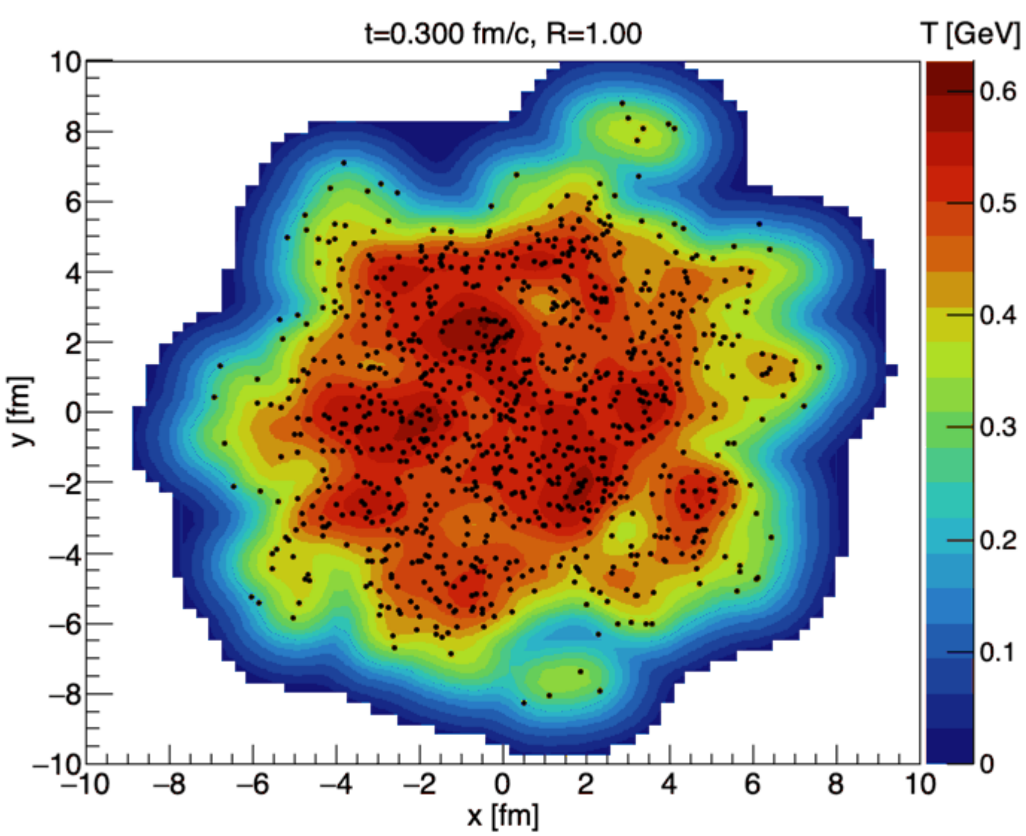
Υ medium response simulation



PRC 97, 014908 (2018)   PLB 801 (2020) 135147

$$\left(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \frac{\partial}{\partial \boldsymbol{x}}\right) f_{\Upsilon}(t, \boldsymbol{x}, \boldsymbol{q}) = -\Gamma^{\text{gluo+inel}}_{\text{diss}}(t, \boldsymbol{x}, \boldsymbol{q})\, f_{\Upsilon}(t, \boldsymbol{x}, \boldsymbol{q})$$

- Boltzmann equation for dissociation of Υ(nS)
- Dissociation cross section at NLO :
  HTL resumption + effective vertex from
  Bethe-Salpeter amplitude
- Thermal width consistent with pNRQCD
  calculations using imaginary potential
  (N. Brambilla et al. JHEP 05 (2013) 130)



- Survival fraction of Upsilons for time step(Δt):

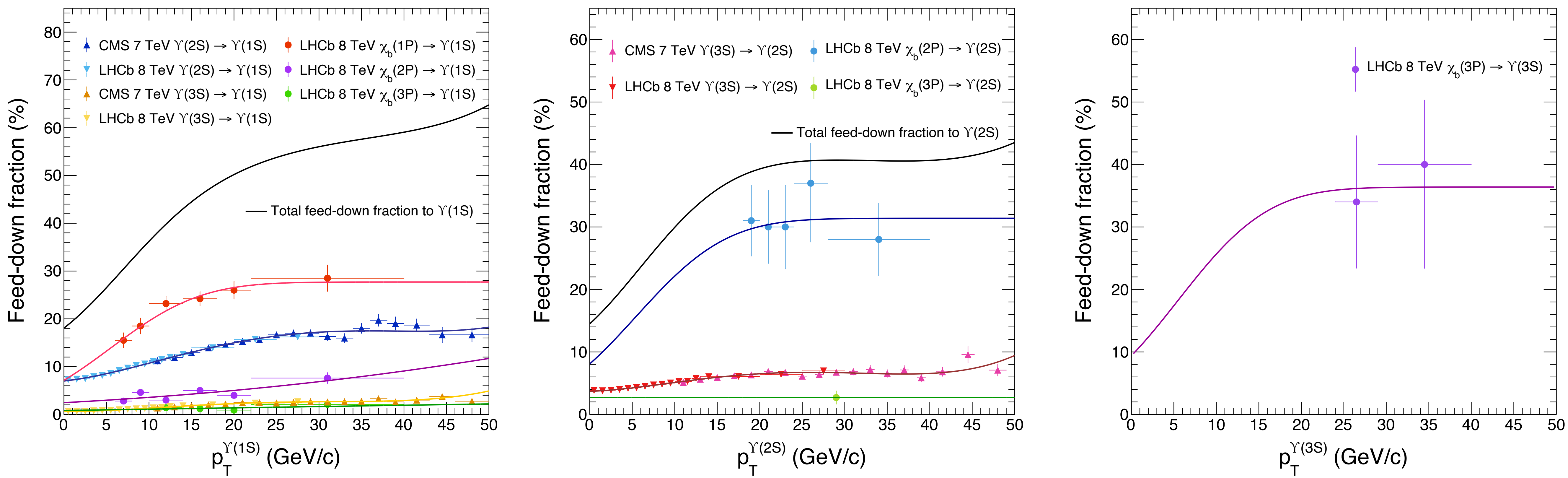
$$\frac{N(t+\Delta t, p_T)}{N(t, p_T)} = e^{-\int_t^{t+\Delta t} dt'\, \Gamma_{diss}(t', p_T)}$$

- Formation time of Υ(1,2,3S) : 0.5/1.0/1.5 fm/c
  boosted vs p_T by lorentz factor γ

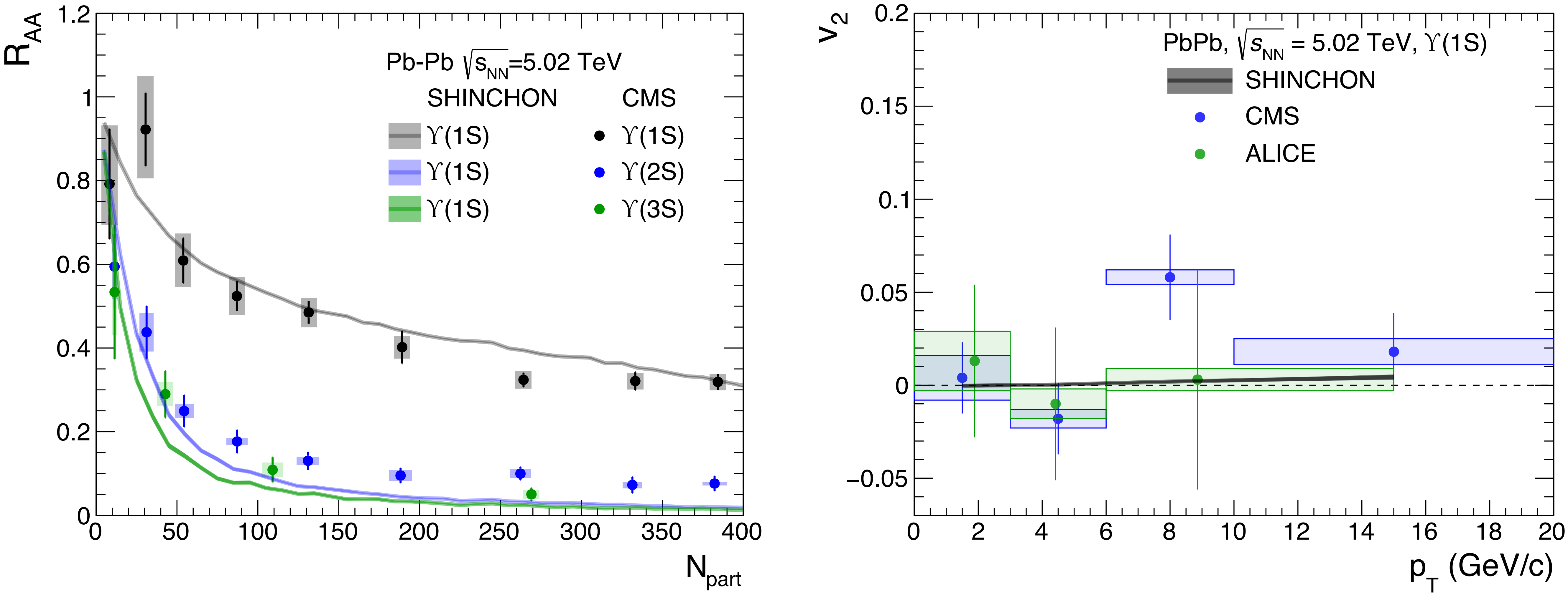
Quarkonium feed-down

- Feed-down contribution for Υ(nS): $R_n(p_T) = \Sigma R_i(p_T) F^{Q_i}_{Q_n}(p_T)$
  - Reweight results w.r.t feed-down fraction from state *i* to *n*

[PLB 749 (2015) 14]
[JHEP 11 (2015) 103]
[EPJC 74 (2014) 3092]



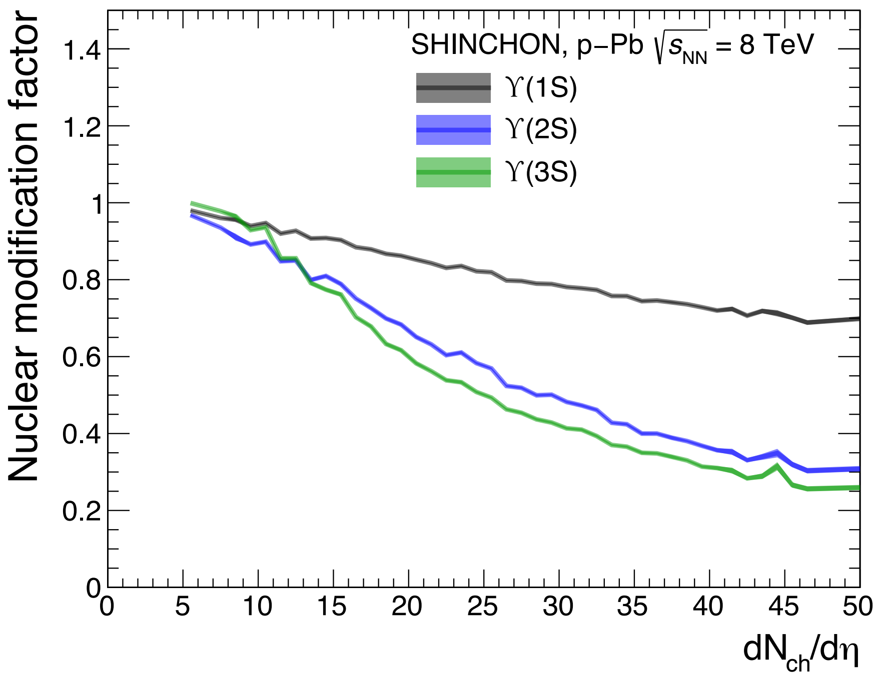
Derivation for PbPb



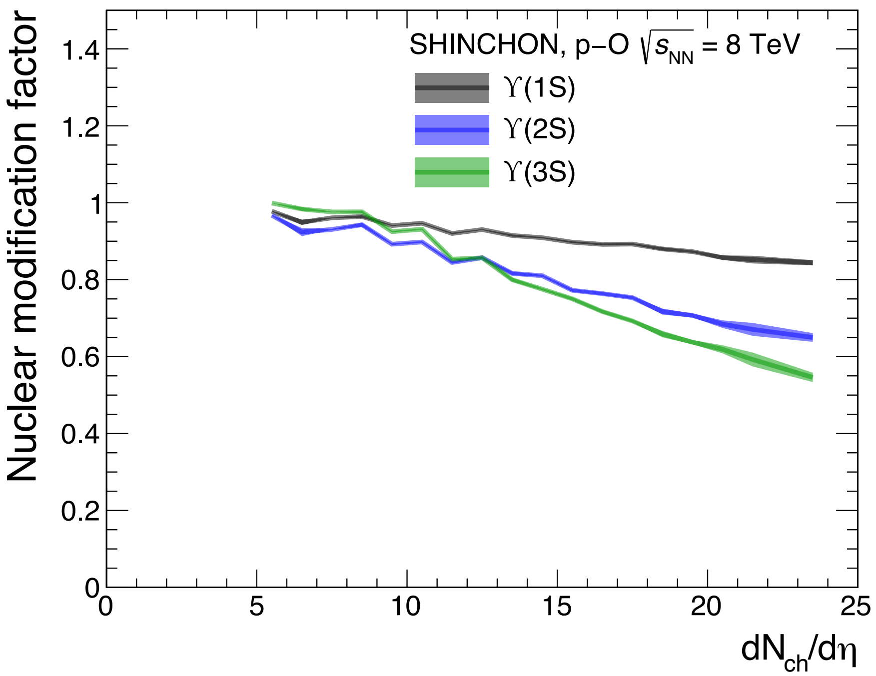
- Dissociation only effects for the illustration of the framework
- N.B no recombination effects included (might be worth for excited states)

Nuclear modification factor

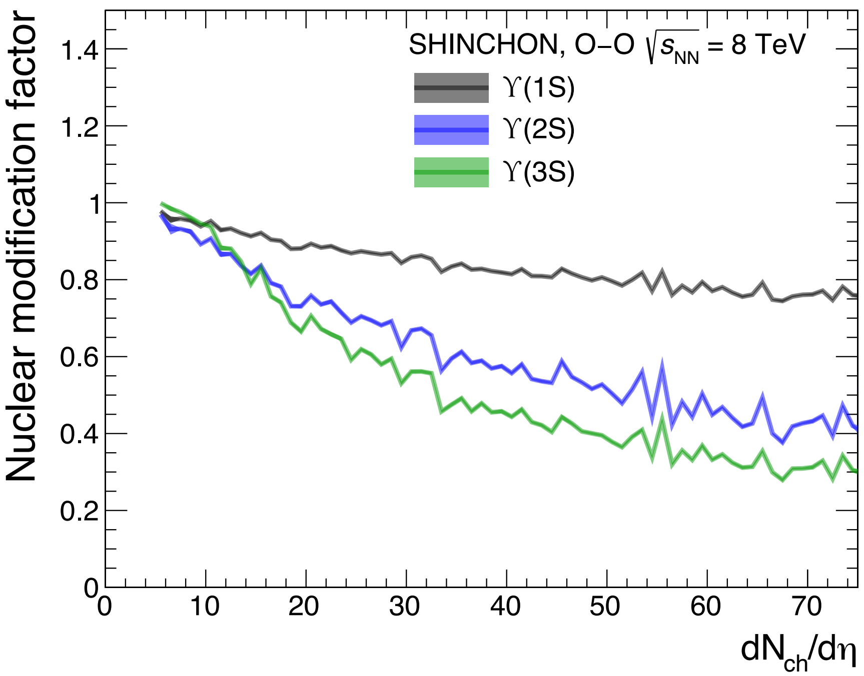
pPb



pO



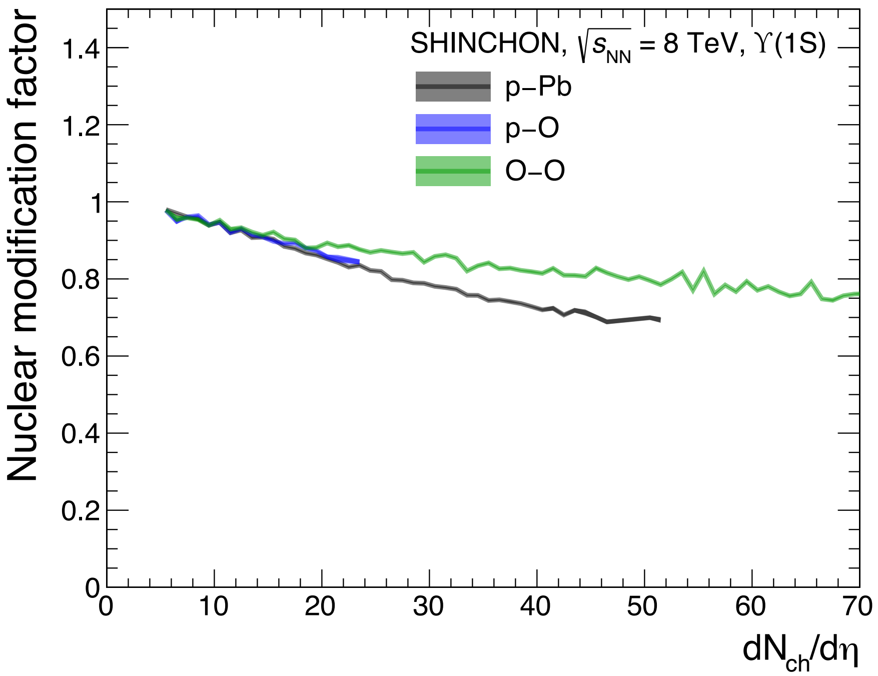
OO



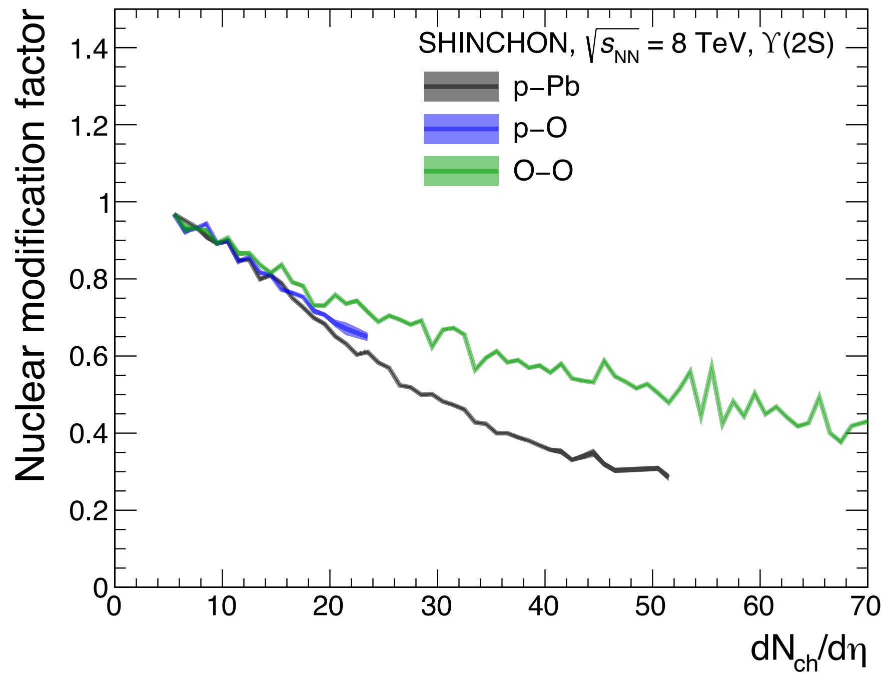
- Sequentially suppressed compared in all systems (pPb / pO / OO @ 8 TeV)

Nuclear modification factor

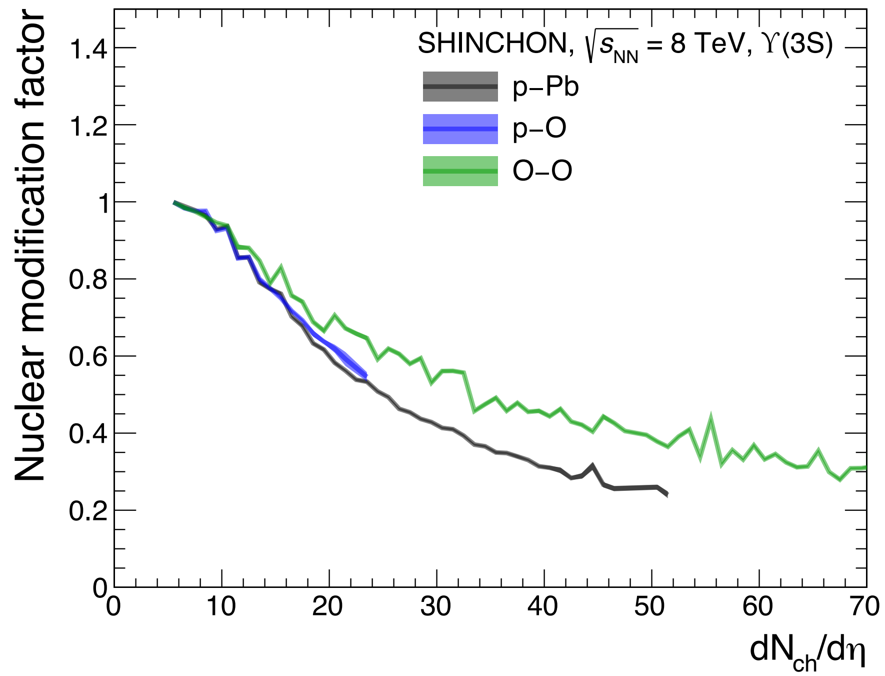
$\Upsilon(1S)$



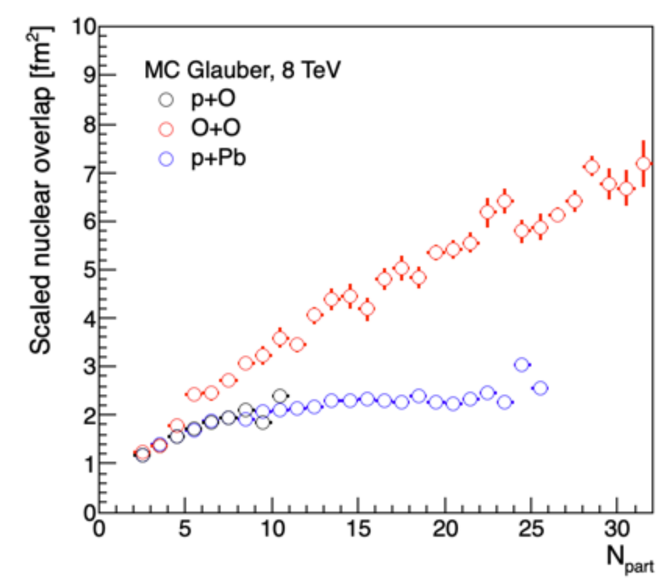
$\Upsilon(2S)$



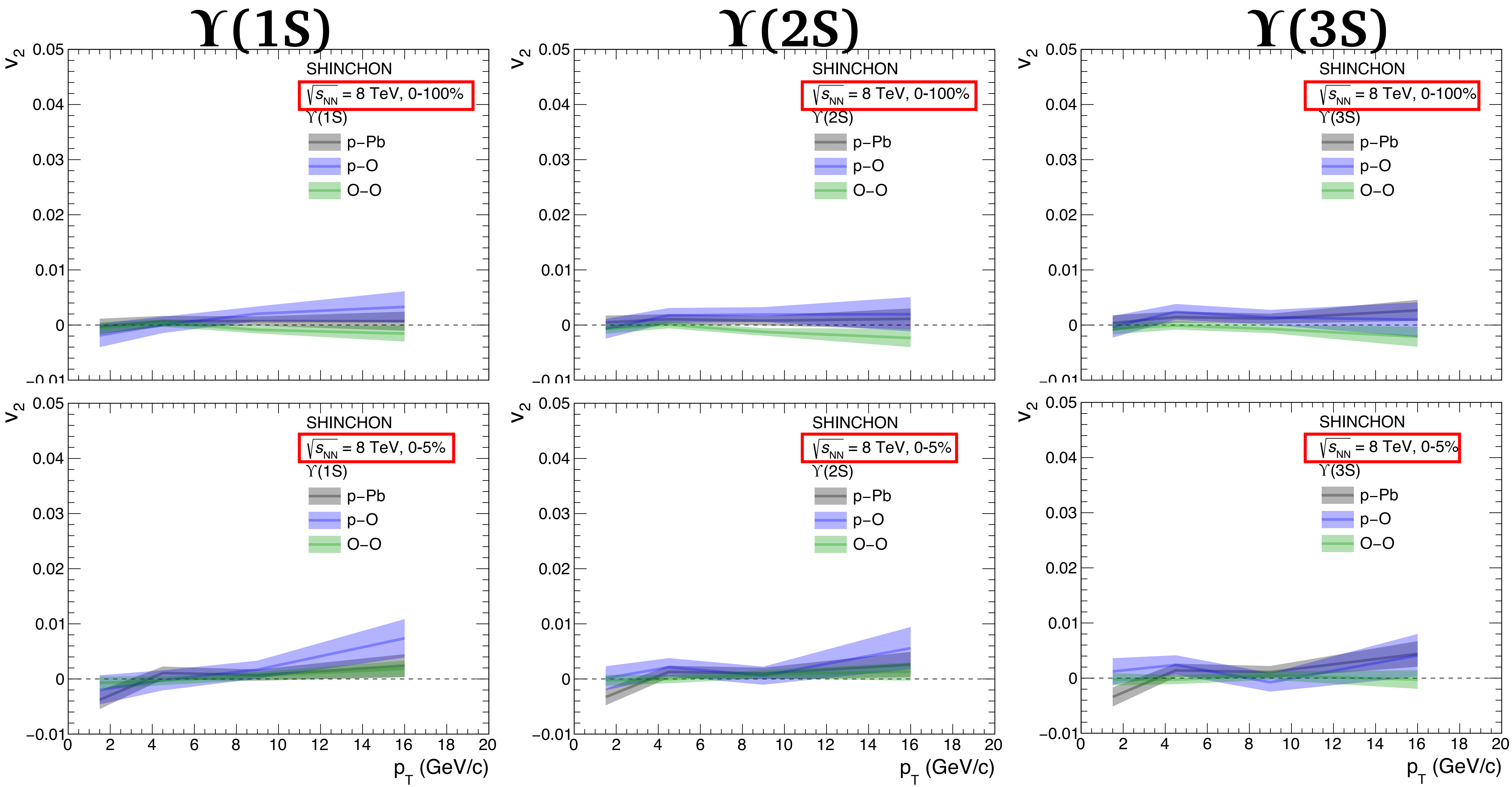
$\Upsilon(3S)$



- Amount of suppression at low-multiplicity : pPb~pO ≥ OO
- Amount of suppression at high-multiplicity : pPb > OO
- System size : OO > pPb > pO vs Energy density : pPb > OO > pO



Elliptic flow



- Small elliptic flow ($v_2 < 0.01$) in the overall p_T region and similar among pPb, pO, OO
- Weak dependence on multiplicity (maybe also for current system size & energy density)

Summary

- ☑ SHINCHON framework developed to perform the medium response of quarkonia
- ☑ Dissociation only effects incorporated to MC Glauber + SONIC in small systems
- ☑ Interesting results in pPb, pO, OO collisions - worth to check with experimental data
- ☑ Future plans to include other effects to make an user-customized framework
  - recombination, nPDF, pre-resonance
  - systematic studies for parameterization
  - different medium simulations e.g. Music 3D hydro
  - comparisons using other theory calculations