Υ(nS) as a golden probe of QGP at sPHENIX

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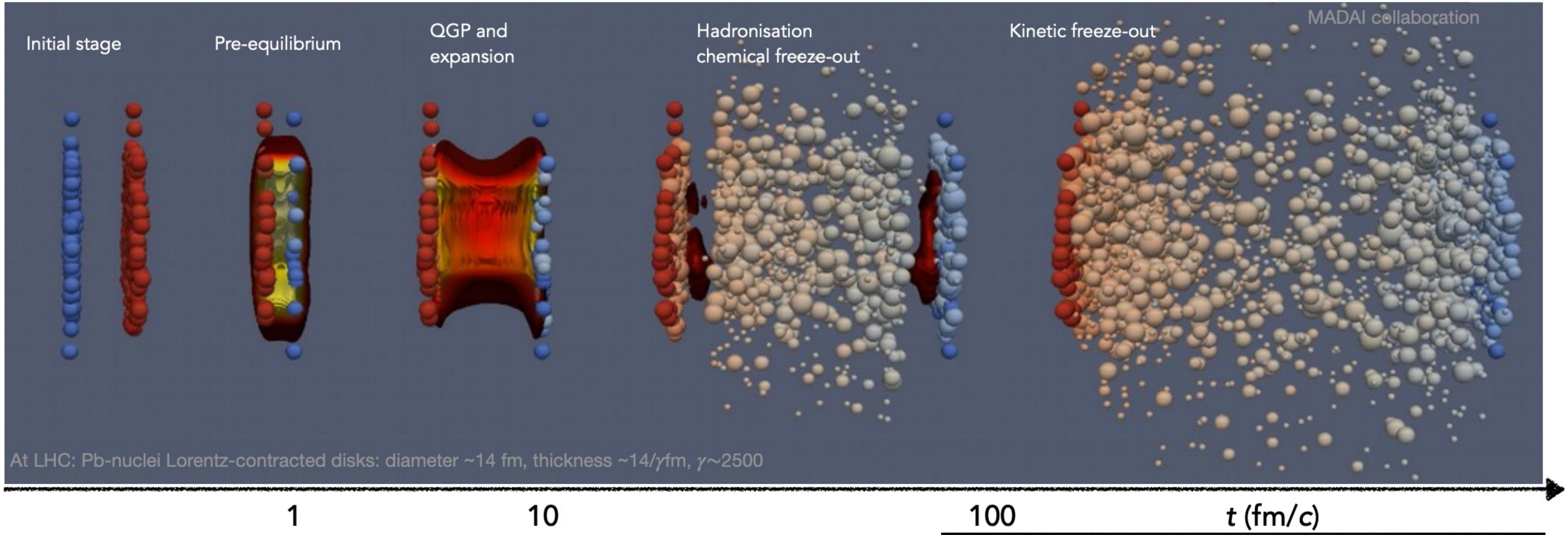
Outline

- Motivation
1) Quark Gluon Plasma (QGP)
2) Heavy quarks and quarkonia
3) Quarkonia to probe QGP

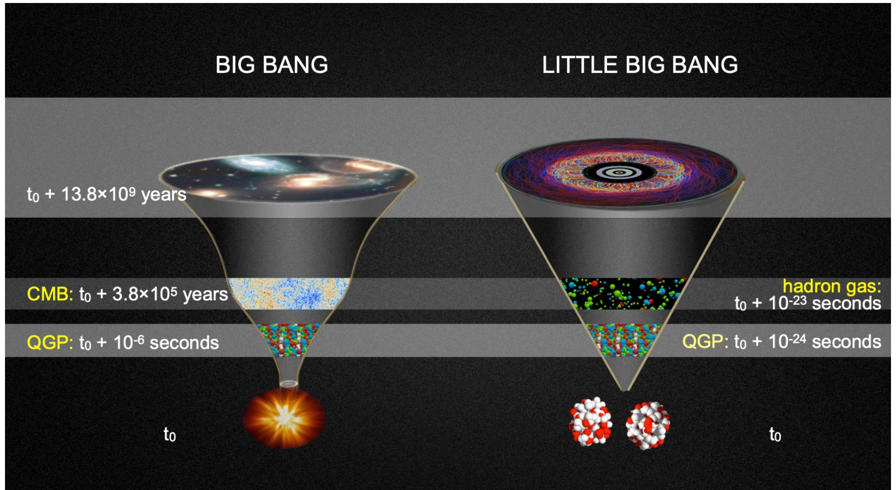
- Quarkonia suppression
1) Υ(nS) $\mathrm{R_{AA}}$ at STAR
2) Υ(nS) $\mathrm{R_{AA}}$ at CMS
3) Comparison between STAR and CMS
- Upsilon Projection at sPHENIX

- Summary

Quark Gluon Plasma



The quark-gluon plasma (QGP) is strongly interacting matter of deconfined quarks and gluons at high energy density and temperature.
The relativistic heavy-ion collisions have been considered as golden probes QGP
We have used the heavy ion collisions to make a little big bang

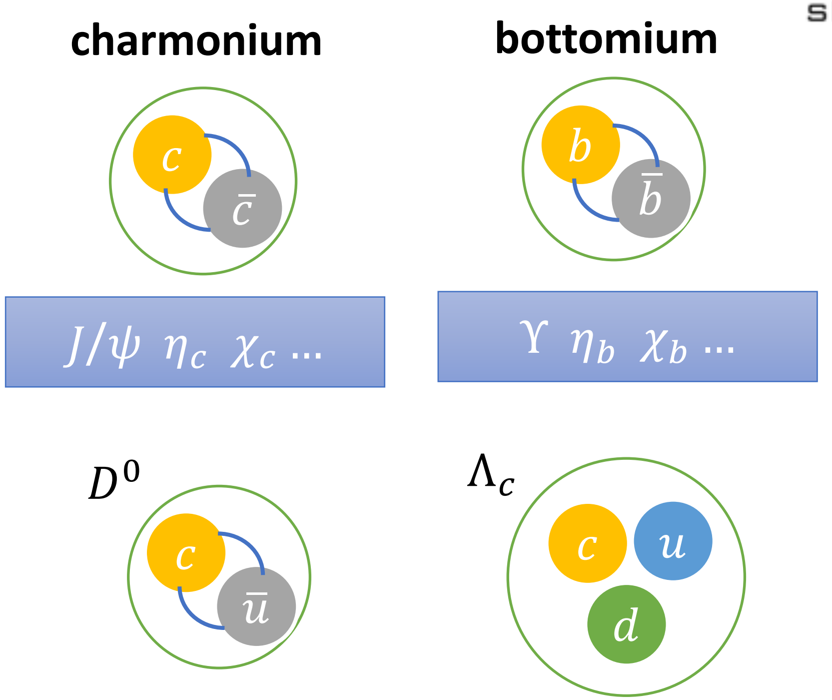


Heavy quarks and Quarkonia

Quarkonium
bound states of $c\bar{c}$ (charmonium) or $b\bar{b}$(bottomium)

Open Heavy Flavor hadrons

Heavy quark bound with light quarks(u,d and s)



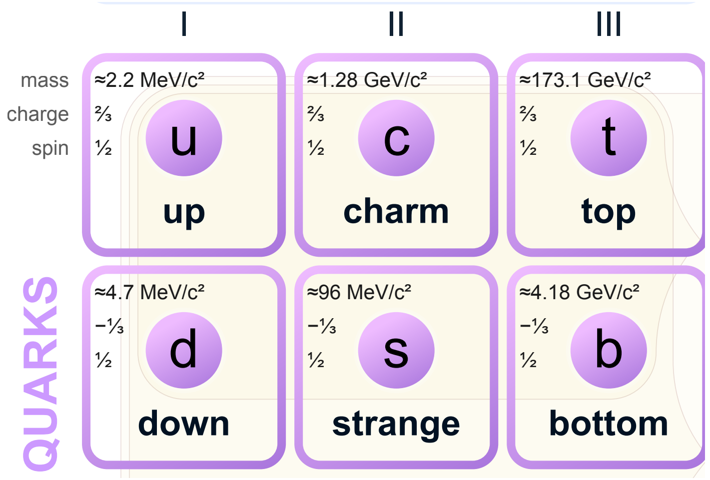
Specific characteristic of Quarkonia

- Small size
 the typical hadron radius ~ 1 fm, but raii of charmonia and bottomia range from **0.1 to 0.3 fm**

- Heavy mass

Since *c* and *b* quarks are very heavy, the binding of the *quarkonium* may be treated **non-relativistically.**

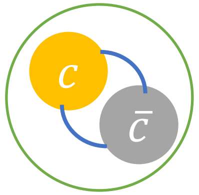
It may be explored via Schrodinger equation.

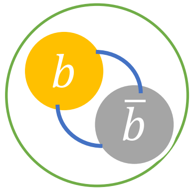


Quarkonia to probe QGP (Why quarkonia?)

- **Why are Quarkonia used to probe QGP?**

  bound states of $c\bar{c}$ (charmonium) or $b\bar{b}$ (bottomium)





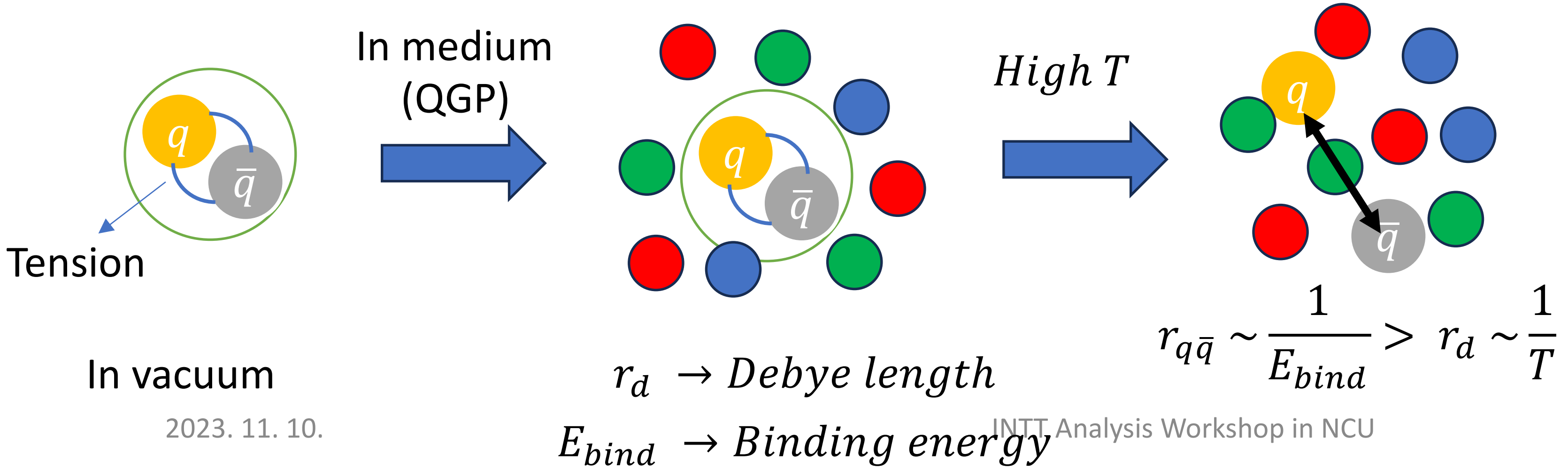
  Quarkonia are produced by hard scattering in the early times of a relativistic heavy-ion collision, thus they experience the entire evolution of the QGP.

- **Quarkonium suppression(melting in QGP with high T)**

  Quarkonium suppression due to the (color) Debye screening

  color-screening effect (screening the potential between quark and anti quark) was proposed as a direct evidence of the QGP.

Debye screening

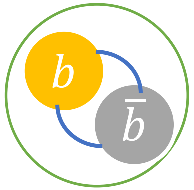


Each quarkonium has its own melting temperature. (own Debye length)

Other effect?
- Regeneration
- Cold nuclear matter(CNM)
- Feed-down

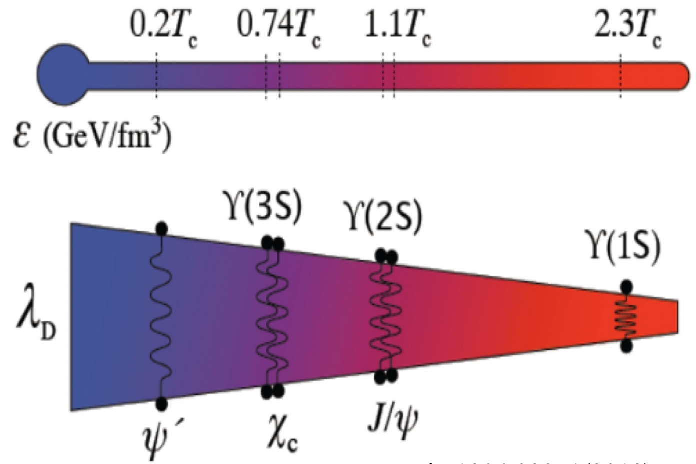
Quarkonia to probe QGP(Why Upsilon?)

- **Then why Upsilons are needed?**



Sequential suppression : Upsilon families have wide range of binding energy. Consequently, upsilon states of different sizes suffer from extremely different levels of suppression in the QGP.

We can compare the amount of the suppression of the Upsilon family!



arXiv:1904.09951(2018)

State	J/ψ	χ_c	ψ (2S)	Υ (1S)	χ_b	Υ (2S)	Υ (3S)
Mass (GeV)	3.10	3.53	3.68	9.46	9.99	10.02	10.36
ΔE (GeV)	0.64	0.20	0.05	1.10	0.67	0.54	0.20
r_d (fm)	0.50	0.72	0.90	0.28	0.44	0.56	0.78
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.6	1.17

1.H. Satz, J. Phys. G **32**, R25 (2006)

- Compared to charmonia, bottomonia are considered cleaner probes than charmonia since the **regeneration contribution** is expected to be smaller for bottomonia due to the smaller production cross section of $b\bar{b}$ quark.

Phys. Rev. C 82 (2010) 064905.
Phys. Rev. C 96 (2017) 054901.

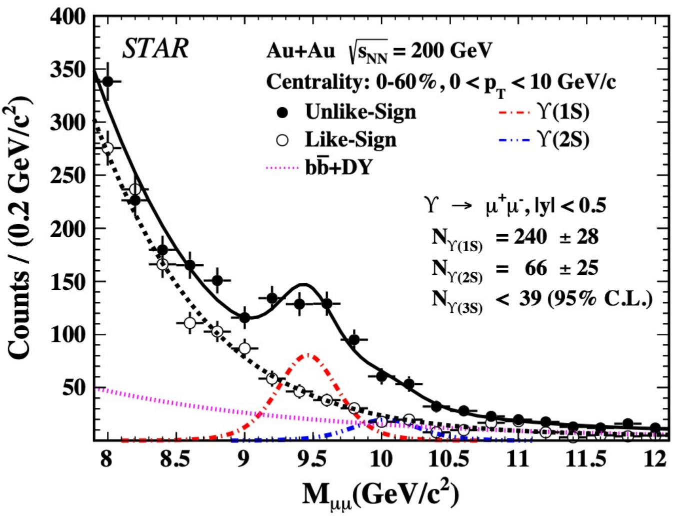
Υ(nS) R_{AA} at STAR; Nuclear modification factor R_{AA}

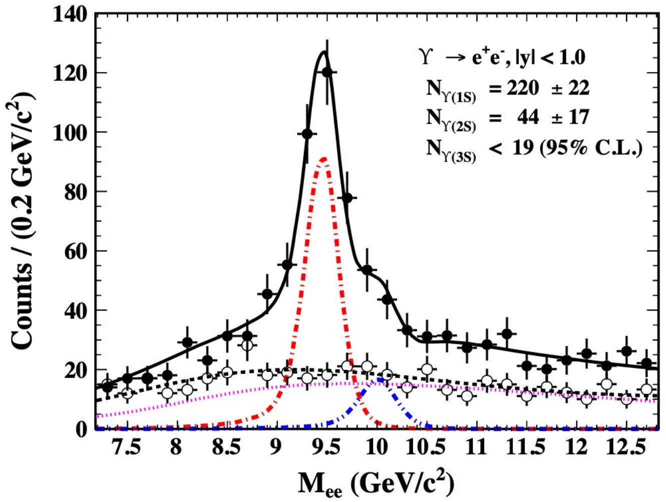
PRL 130 112301(2023)

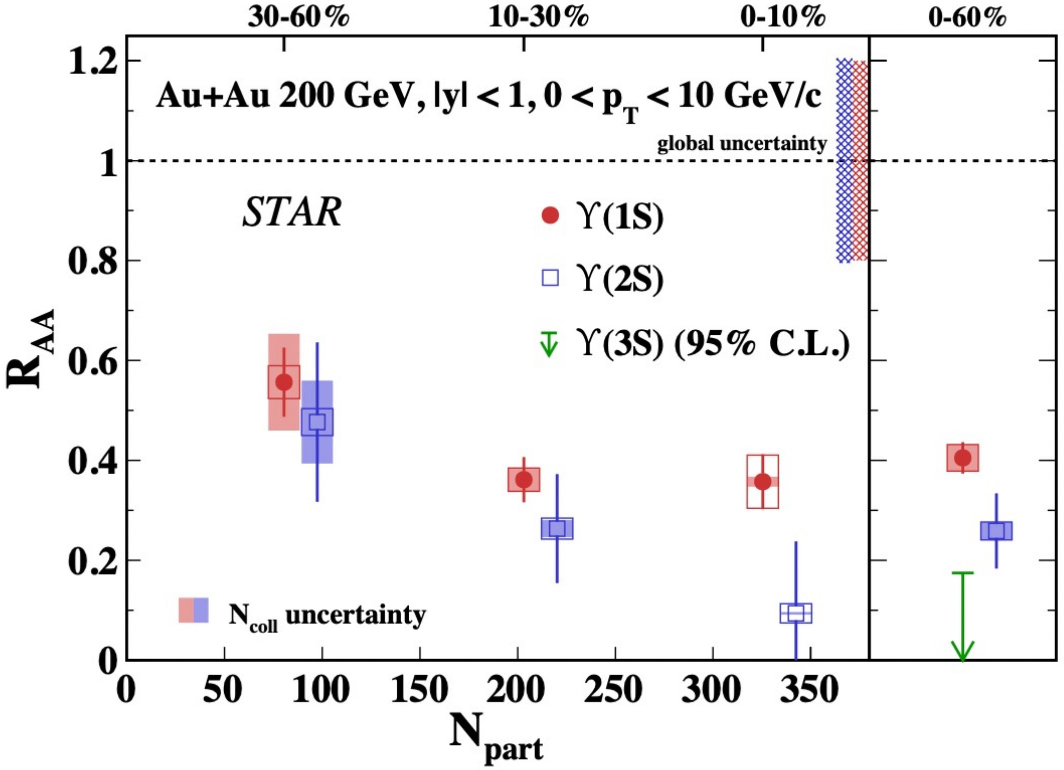
$$R_{AA} = \frac{dN^{AA}_{\Upsilon_{(nS)}}/dp_T}{< N_{coll} > dN^{pp}_{\Upsilon_{(nS)}}/dp_T}$$

- The ratio of the production cross-section in pp (N_{pp} , σ_{pp}) and the production cross-section in AA (N_{AA}, σ_{AA}) collisions normalized by the binary collision (Ncoll)

STAR measured R_{AA} by using the two dilepton channels (dimuon, di-electron)







- Significant suppression for different Upsilon states is observed.
- Suppression gradually increase towards central collision.
- Results show sequential suppression patten.

But for Υ(3S), only upper limit is provided by STAR.

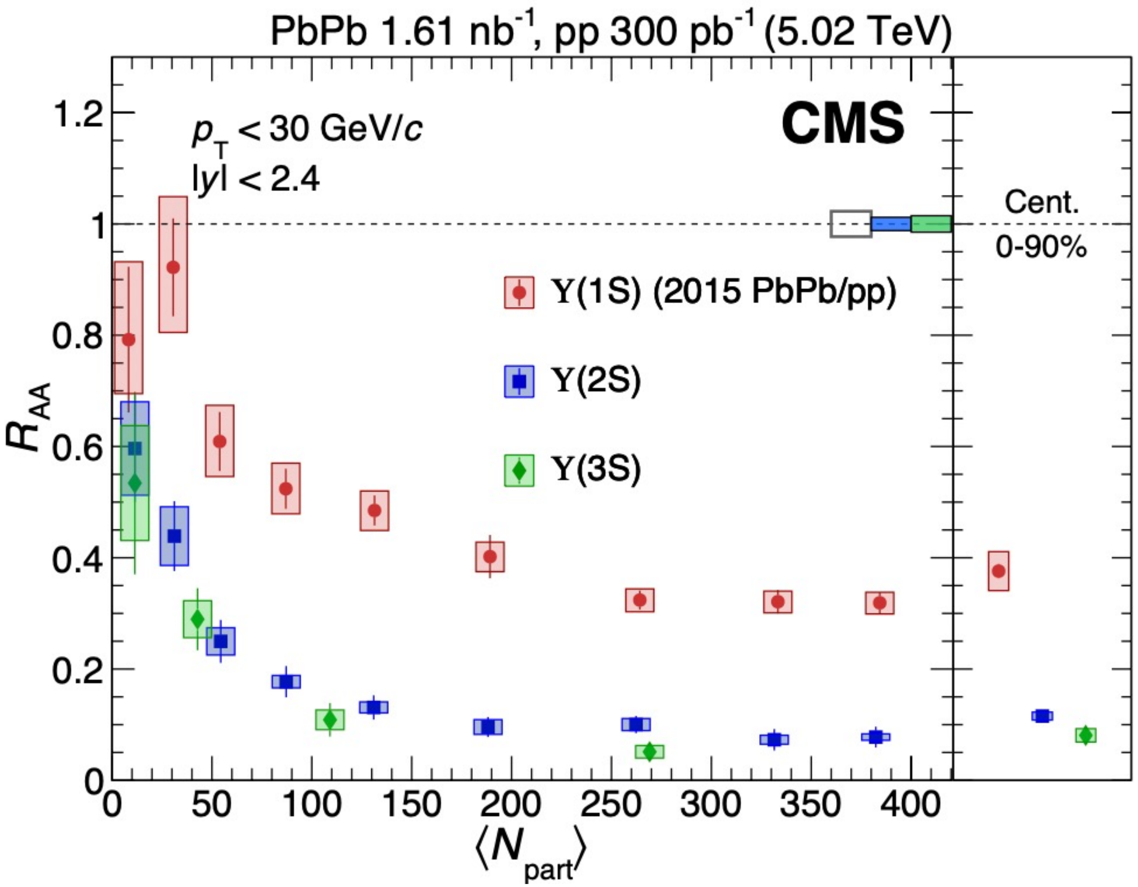
Υ(nS) R_{AA} at CMS

arXiv:2303.17026(2023)

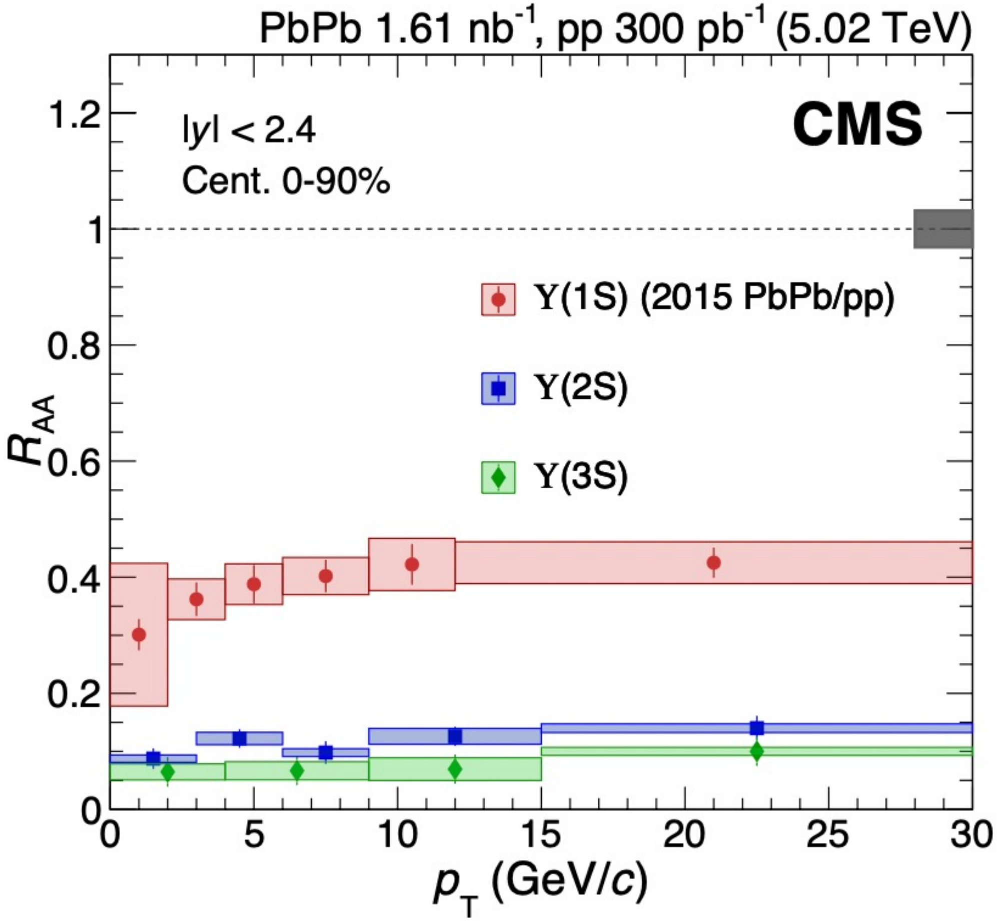
First observation of Υ(3S) in PbPb Collision

Sequential suppression R_{AA} : Υ(1S) > Υ(2S) > Υ(3S)

No significant P_T dependence of R_{AA}



No significant P_T dependence of R_{AA}



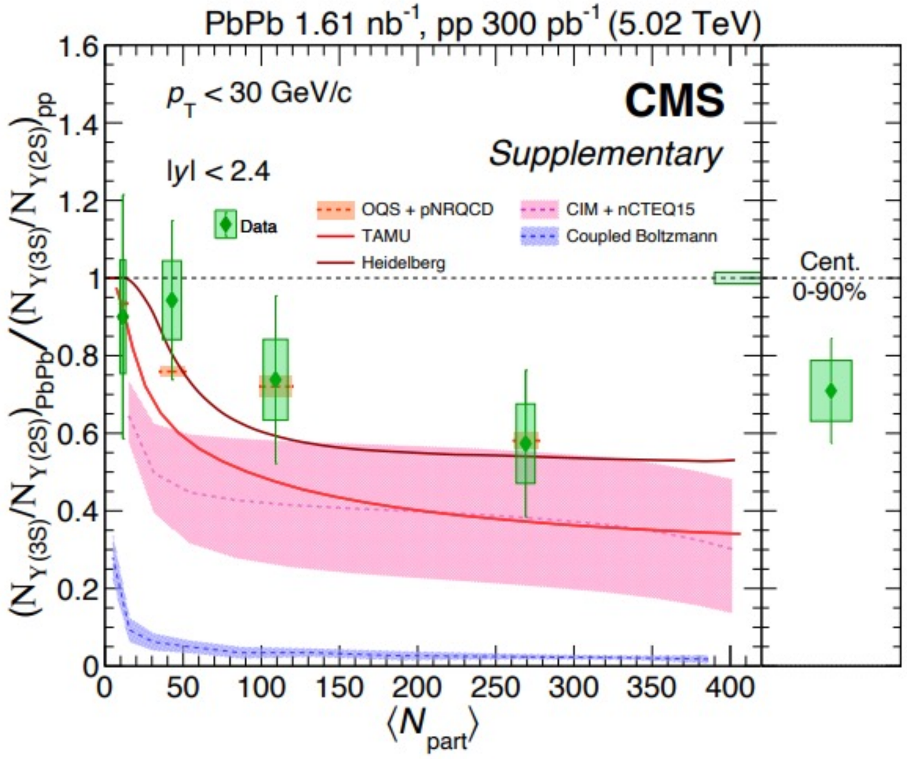
Double ratio Υ(3S)/Υ(2S)

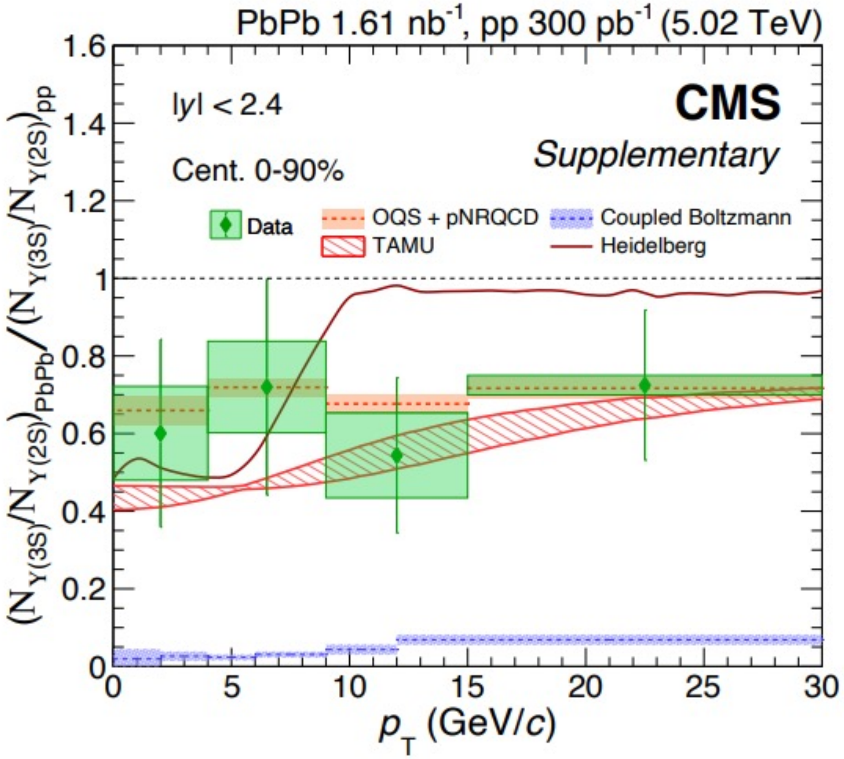
arXiv:2303.17026(2023)

Significant differences among model calculations

Double ratio < 1 means heavier suppression for **Υ**(3S) than **Υ**(2S) particularly for central events.
But the data set still show relatively large uncertainties.

New measurement required for strong constraints to the models.



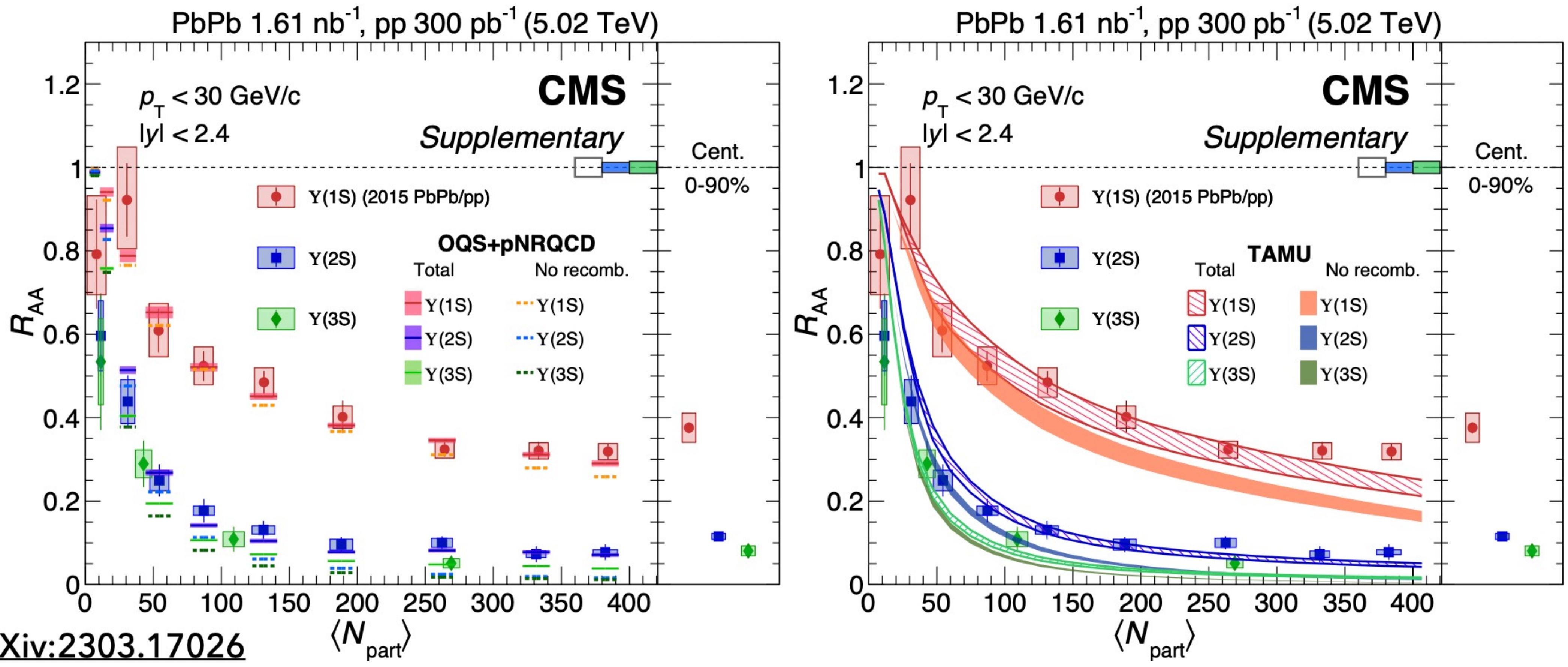


Regeneration effect at CMS

Dashed line represent no regeneration(recombination) effect

Role of regeneration(recombination) is not negligible even for bottomonia.

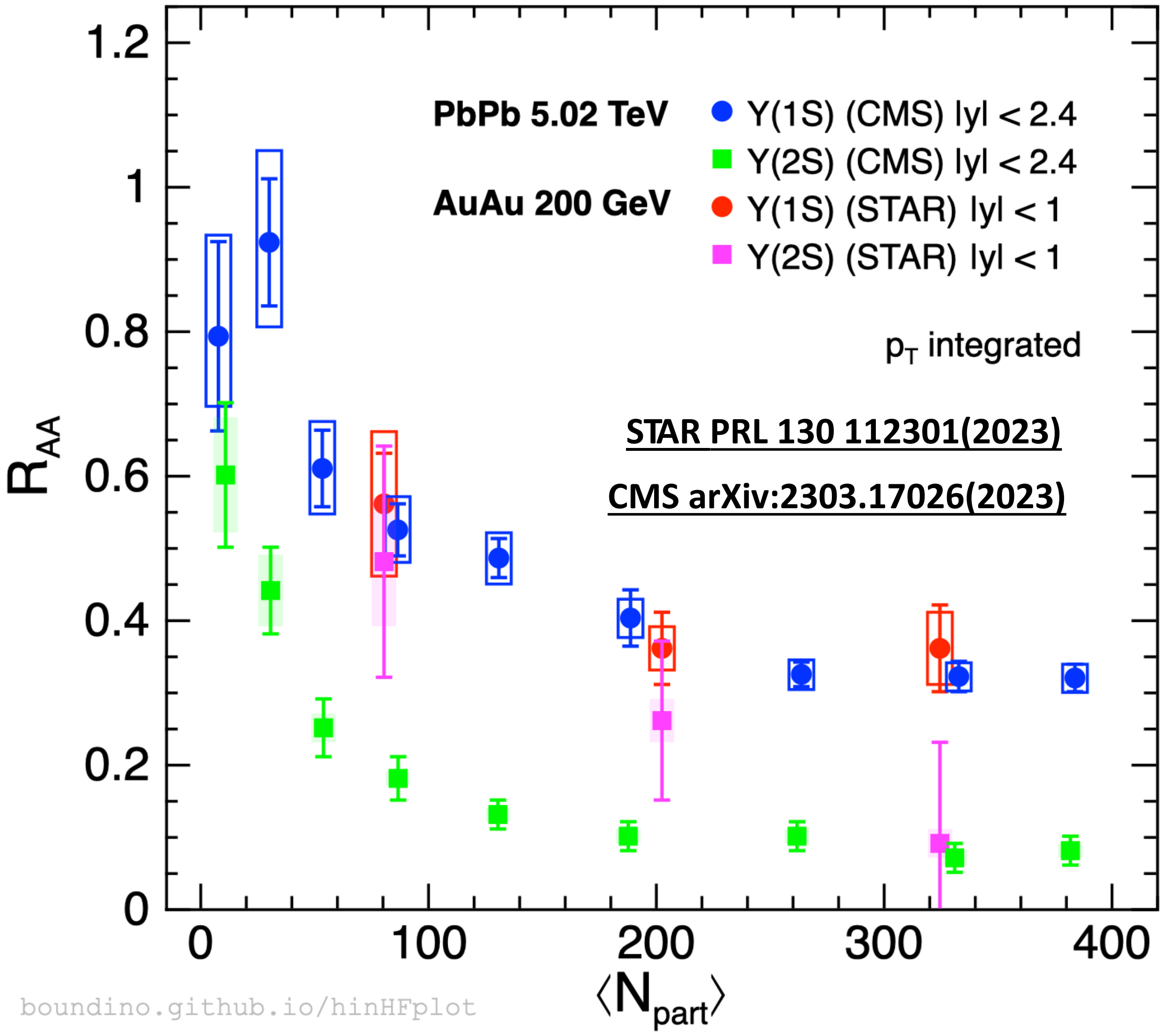
We need more clear probe! RHIC



arXiv:2303.17026

Presented at ATHIC 2023

Comparison between STAR and CMS



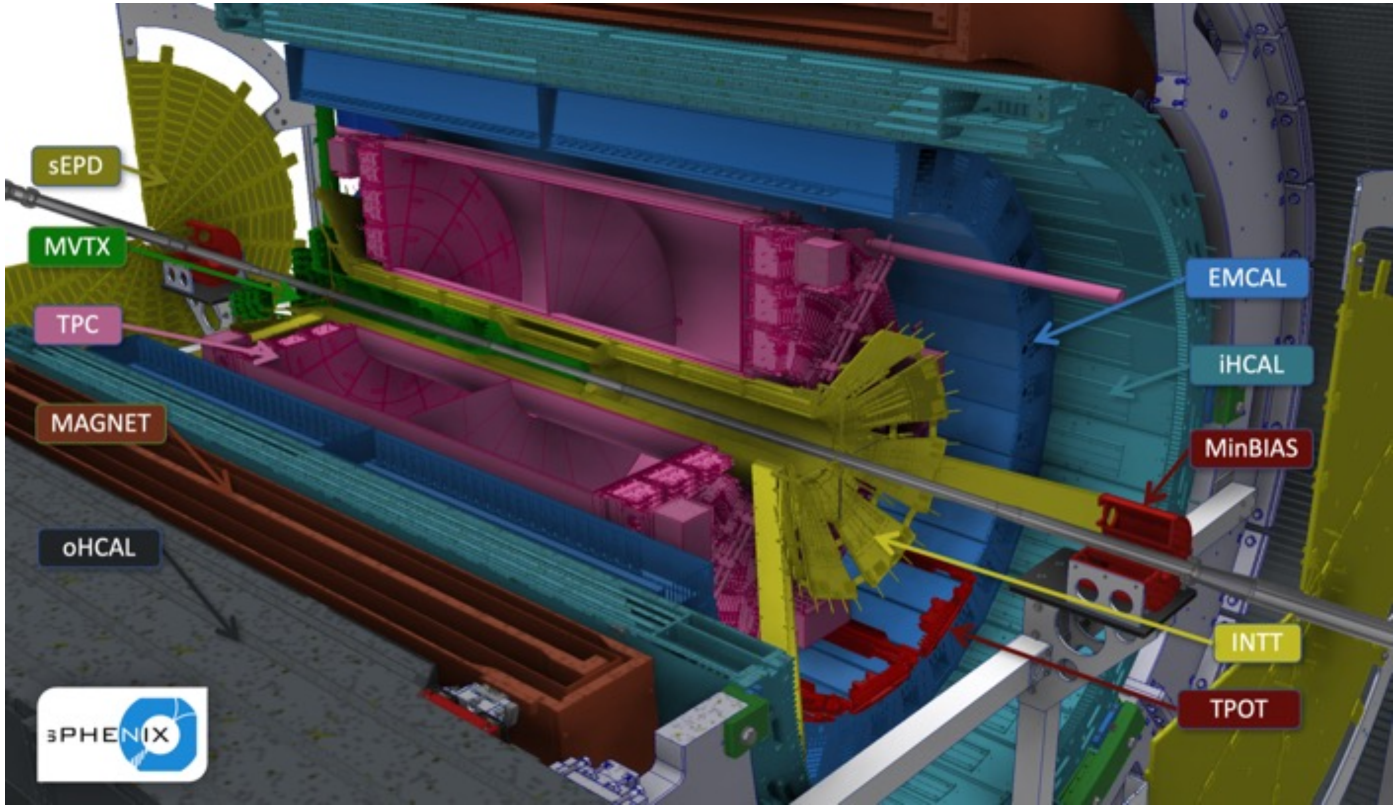
Behavior of Υ(1S) looks similar.

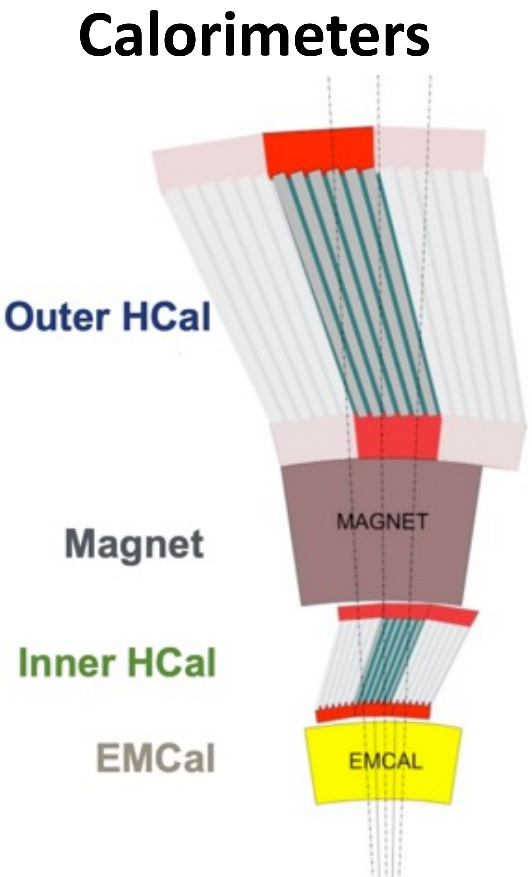
Υ(2S) different shape.

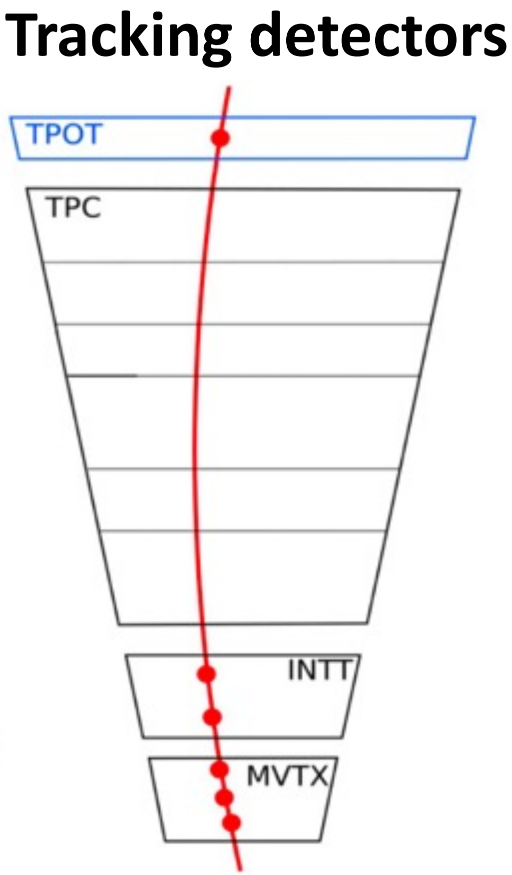
It might be the key..
But we still can't understand well.

New measurement required for strong constraints to the models.

sPHENIX Detector system





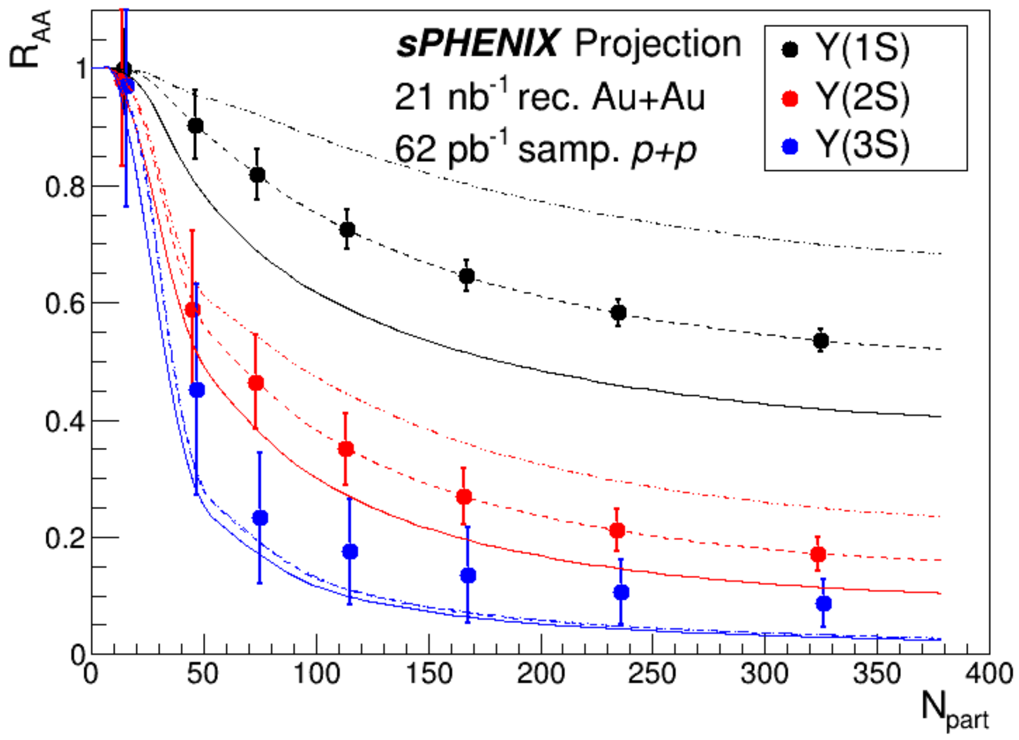


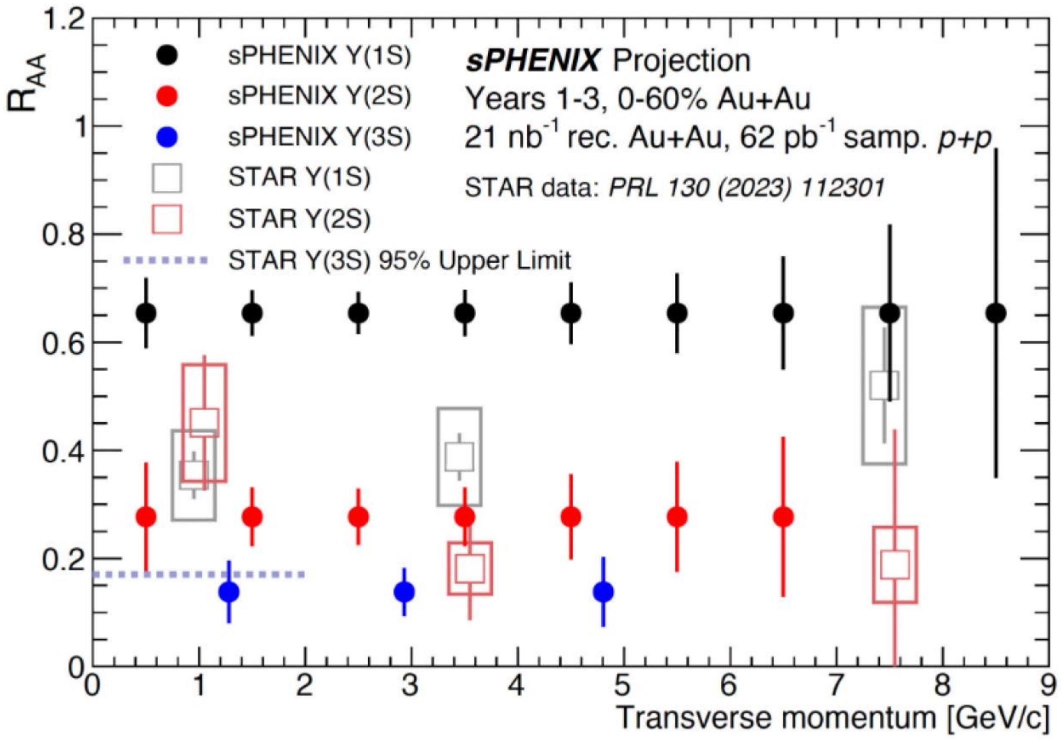
- ❑ Coverage improvement
  |η| < 0.35 & 0.5π per arm for φ (PHENIX)
  |η|≤1.1 & 2π for φ (sPHENIX)

- ❑ High data rates : 15 kHz for all subdetectors

Improved coverage and improved tracking system allow us crucial key for Upsilon Physics.

Upsilon Projection at sPHENIX





- Three year plan(Beam User Proposal) were assumed to evaluate the projection.
- sPHENIX has the unique opportunity to discover the Y(3S) suppression at RHIC.
- Y(3S) at RHIC will be cleaner probe then LHC! (no regeneration)

Summary

- To probe QGP, we have proposed to use the quarkonia as the thermometer.

- Upsilon states can give us extremely wide range of temperature information of QGP comparing to chamonium.

- Since recent result at CMS indicates regeneration of **Υ**(3S) is non-negligible, proposed **Υ**(nS) measurement at sPHENIX will give us a golden chance to explore the detail.

Thank you!

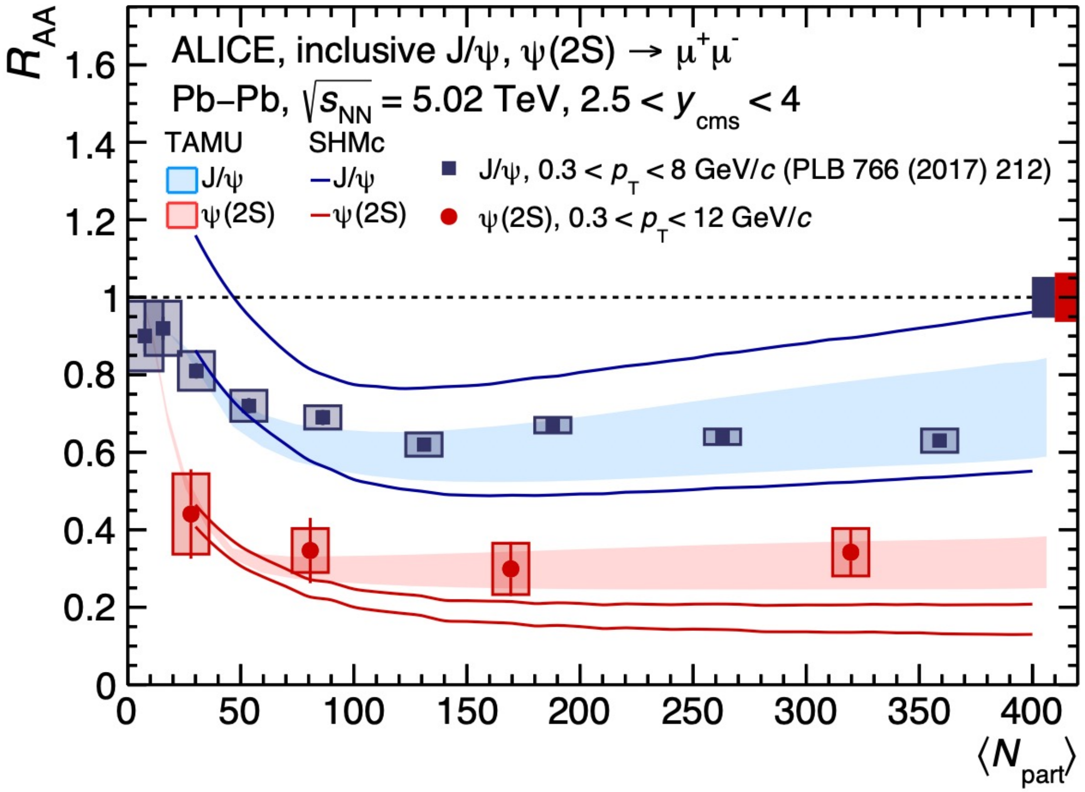
sPHENIX detector

On site BNL crew (Post-Doc, Students)

Backup

ψ(2S) suppression

Suppression of quarkonia usually measured via $\mathrm{R_{AA}}$



$$\mathrm{R_{AA}} = \frac{dN^{AA}_{\Psi_{(2S)}}/dp_T}{< N_{coll} > dN^{pp}_{\Psi_{(2S)}}/dp_T}$$

- The ratio of the production cross-section in pp (σ_{pp}) and the production cross-section in AA (σ_{AA}) collisions normalized by the binary collision (Ncoll)

Charmonia also have sequential suppression.

What about the Upsilon?
It may allow us to have more understanding with neglectable regeneration effect.

Soft / Hard sector

• Soft Sector

Particles below a certain p_T threshold (e.g. 2 GeV/c)

Small momentum transfer

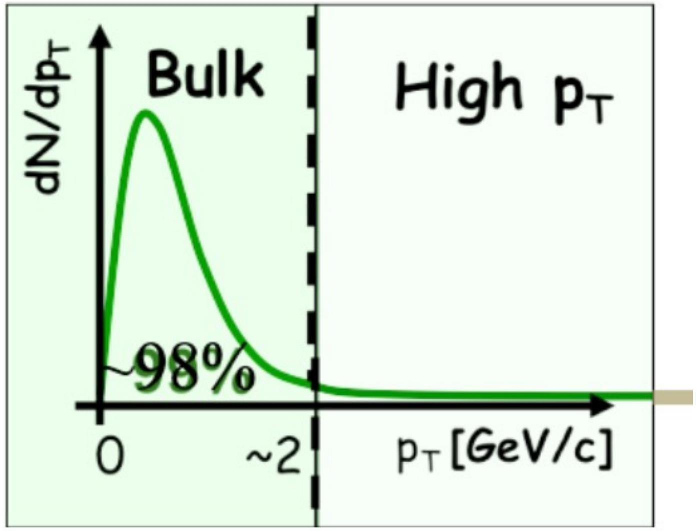
perturbative QCD not applicable

• Phenomenological models, transport models, statistical models

Characterize global (bulk) properties of heavy-ion reactions

Sensitive to the late stage of the reaction

Probe hadronization features



• Hard Sector

High pT particle production

Heavy quark cross-sections; heavy particles production (charm, beauty) ,Jets

pQCD applicable

with addition of parton distribution and fragmentation functions

≈ 98% of all particles are produced with $p_T < 2$ GeV/c.

≈ 80% of all particles are pions, ≈ 13% are kaons, and ≈ 4% are protons.

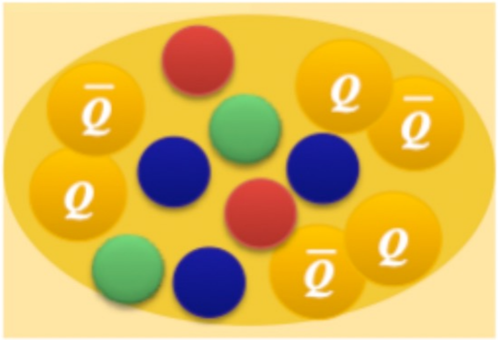
More about other effect

Cold nuclear matter effects: modification of parton distribution function of nuclei relative to proton and nuclear absorbtion.

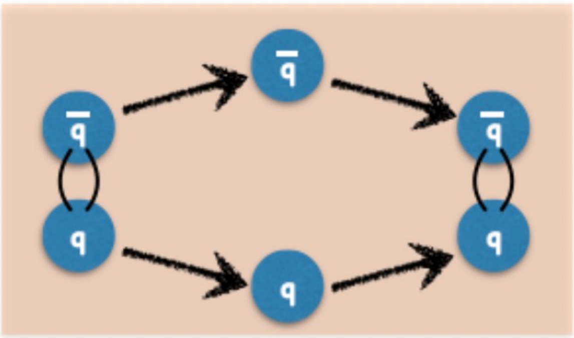
Regeneration : coalescence of statistical/uncorrelated quarks or recombination of heavy-quark pairs from an original dissociated quarkonium.

Feed-down : production of ground state and sequential suppression of higher states.

Comoving effects and dissociation : Inelastic scattering process causes the breakup of the quarkonia.

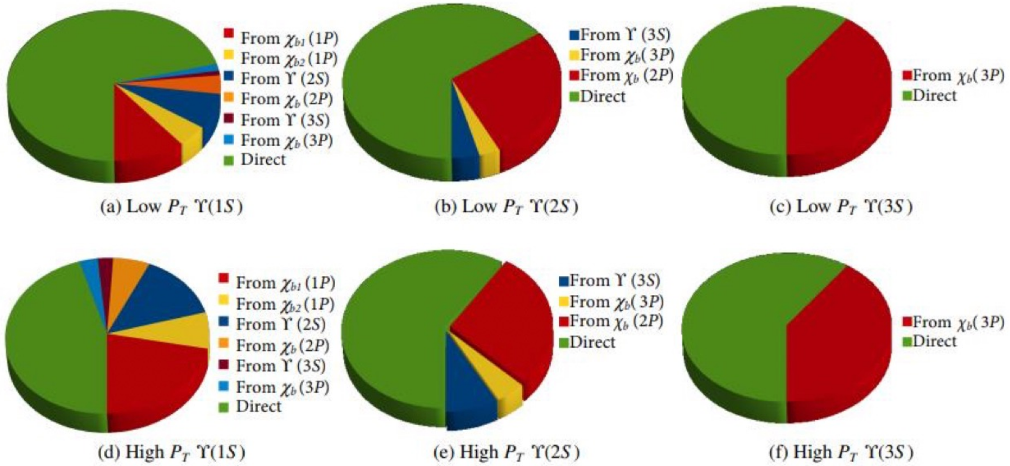


statistical/uncorrelated regeneration



Correlated regeneration

Feed-down



J.P. Lansberg, Phys. Rep. 889(2020)

Proposed run schedules (2022)

sPHENIX

sPHENIX BUP2022 [sPH-TRG-2022-001]

~~**Year-1 (Au+Au)**~~
Done!
Commissioning, calibration
HI measurements

Year-2 (pp & pAu)
Reference for HI measurements & **polarized p+p, p+A measurements for Cold QCD(Spin Physics)**

Year-3 (Au+Au)
High statistics HI measurements

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\|z\| < 10$ cm	Samp. Lum. $\|z\| < 10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

Proposed run schedules (2023)

sPHENIX BUP 2023

• *Measurements in p+p data.*
39 pb$_{-}$ of sampled / 3.9 pb$_{-1}$ streaming *p+p* data(2023)
the 62 pb$_{-1}$ and 6.2 pb$_{-1}$, respectively(2022)
The expected statistical uncertainties in both calorimeter-triggered (i.e. photons and jets) and MB-triggered (i.e. heavy flavor) observables should be **increased by approximately 25%.**

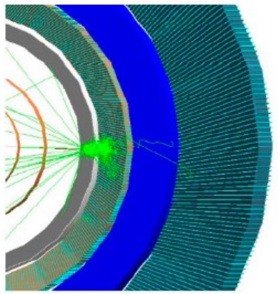
• *Most measurements in Au+Au data*,
6.3 nb−1(2023) of recorded events the 21 nb−1(2022)
The expected statistical uncertainties for these observables should be increased by approximately 80%.

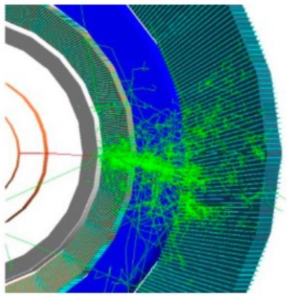
Species	$\sqrt{s_{NN}}$ [GeV]	Physics Weeks	Min. Bias Rec. Lum. $\lvert z \rvert < 10$ cm	Calo. Trigger Lum. $\lvert z \rvert < 10$ cm
Run-2024, Scenario A, 6 cryo-weeks Au+Au + 20/24/28 cryo-weeks *p+p*				
Au+Au	200	n/a	n/a (Commissioning running)	
p+p	200	13/17/21	0.34/0.44/0.54 pb^{-1} [@ 5kHz] 2.3/3.1/3.9 pb^{-1} [10%-str]	23/31/39 pb^{-1}
Run-2024, Scenario B, 20/24/28 cryo-weeks *p+p* + 6 cryo-weeks Au+Au				
p+p	200	9/13/17	0.23/0.34/0.44 pb^{-1} [@ 5kHz] 1.5/2.3/3.1 pb^{-1} [10%-str]	15/23/31 pb^{-1}
Au+Au	200	3	0.4 nb^{-1} (3B events)	not needed
Run-2025, 24/28 cryo-weeks				
Au+Au	200	20.5/24.5	5.2/6.3 nb^{-1} (35B/43B events)	not needed

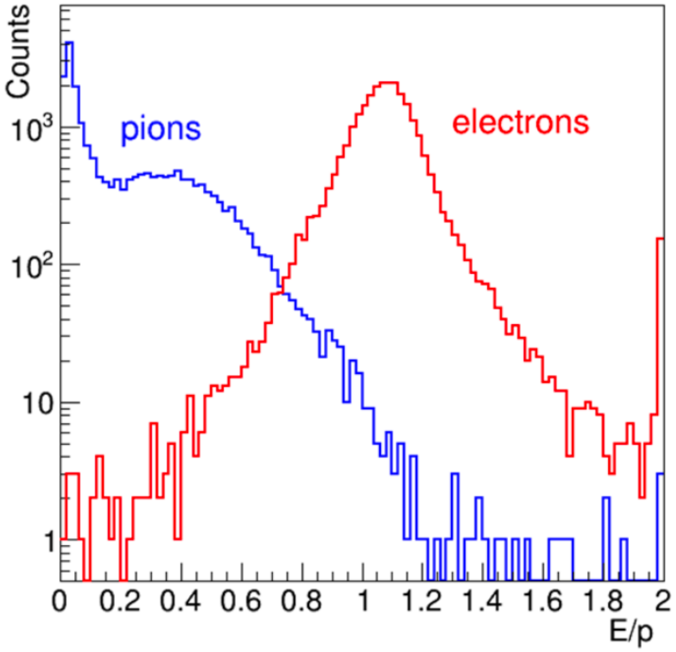
Upsilon Signal extraction

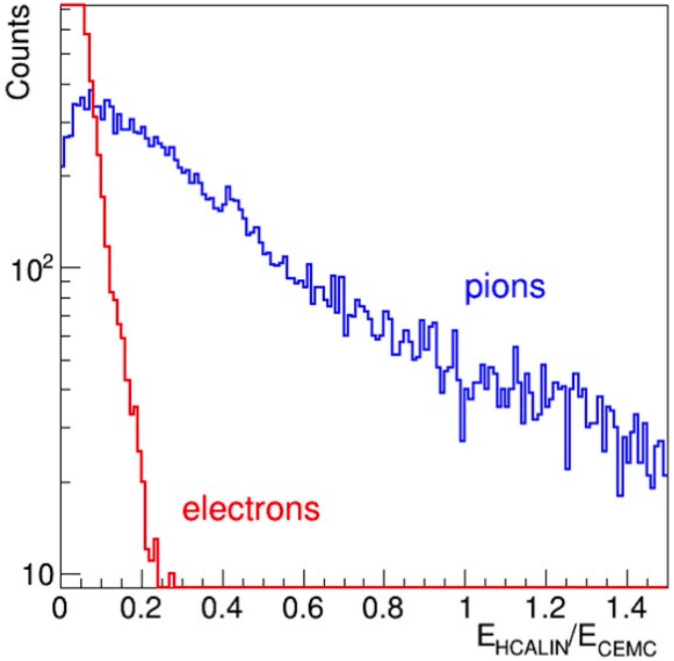
- P_t > 2 GeV/c cut used
- Electrons deposit most energy in EMCal, hadrons in HCal
- Good rejection power, but overlaps with E/p rejection in EMCal
- Requires sophisticated multi-variable analysis

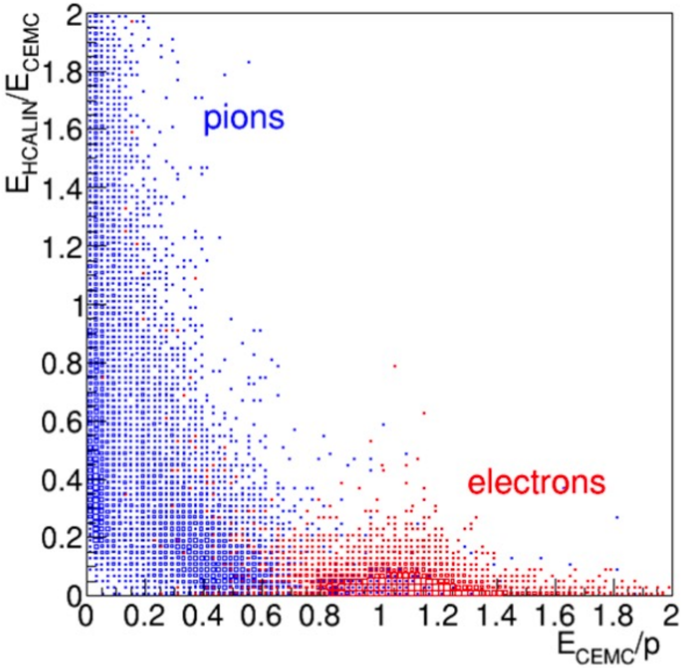
eID stragies : Individual variable anaylnis & multiple variable analysis
Variable : E_{EMCal}/p, E_{inHCal} / E_{EMCal} , vertex information, shower shape


electron


hadron



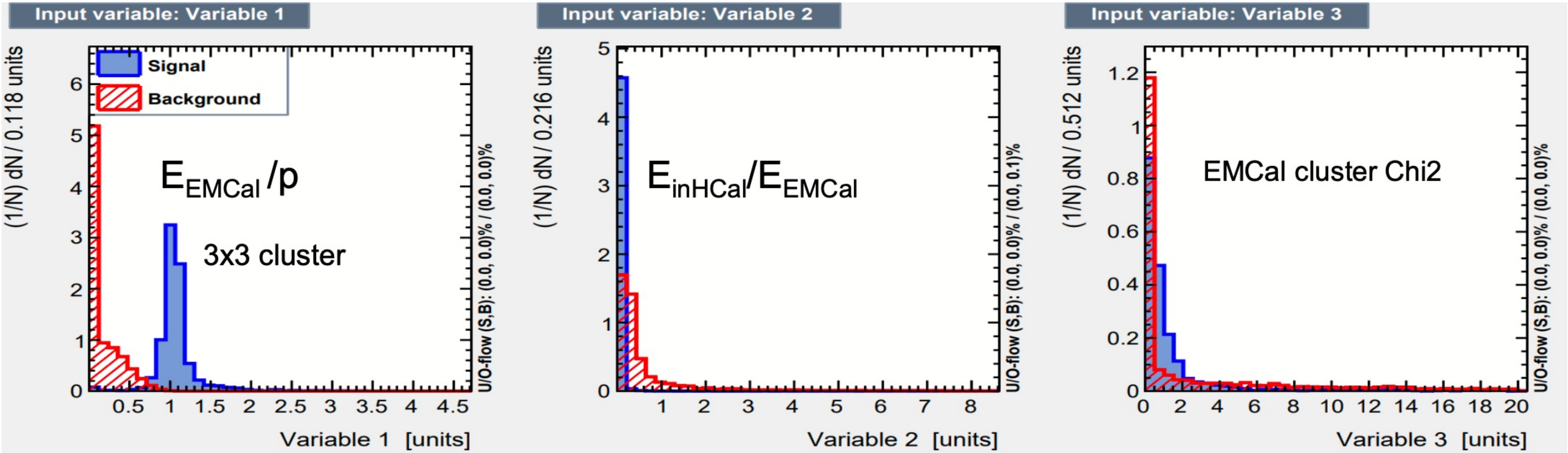


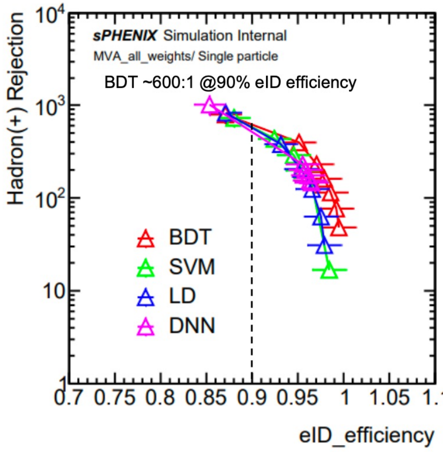


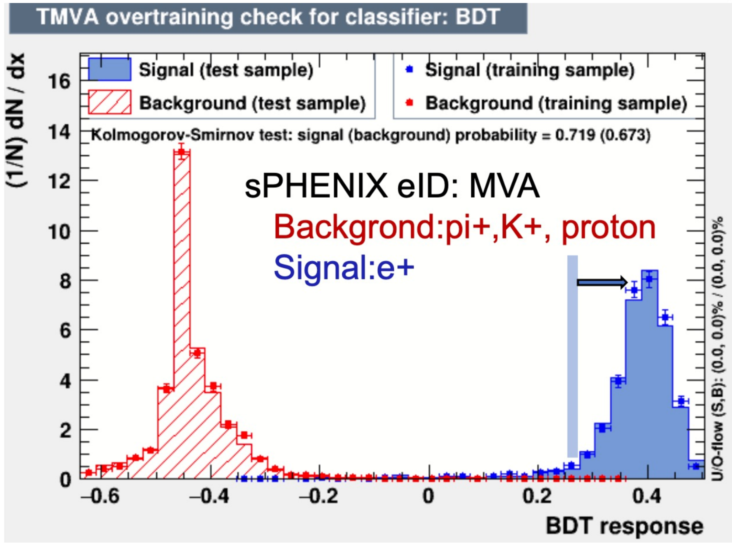
sPHENIX Summer School
Given by Sasha Lebedev (ISU)

Upsilon Signal extraction

Machine learning algorithm(BDT) used to classify the electron source and background.







sPHENIX Summer School
Given by Sasha Lebedev (ISU)

Upsilon Signal extraction

sPHENIX p+p simulation : $\Upsilon(nS) \rightarrow e^+e^-$ **sPHENIX Au+Au simulation : $\Upsilon(nS) \rightarrow e^+e^-$**