Quarkonia measurements in heavy ion collisions

Dong Ho Moon
On behalf of the CMS collaboration
Chonnam National University

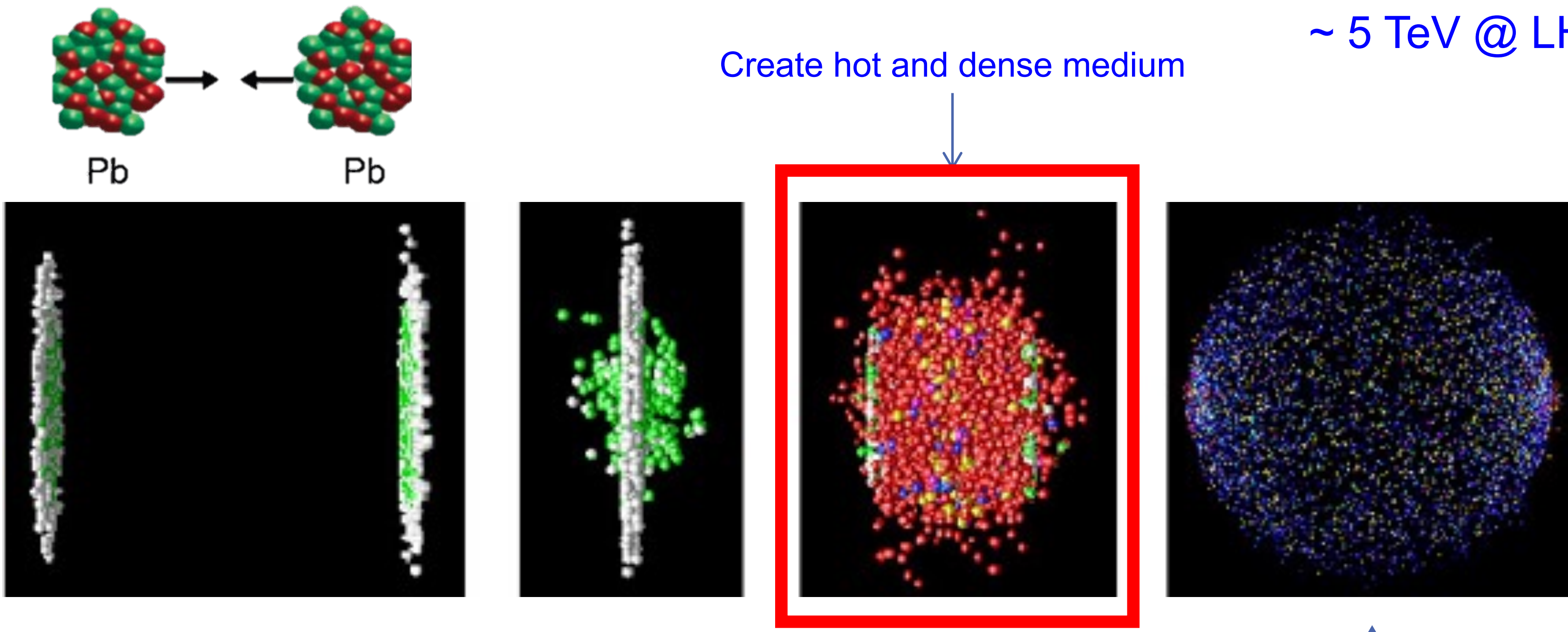
2023/08/09 RdV30 @ Quy Nhon (Viet Nam)
Rencontres du Vietnam 30th Anniversary:
Windows on the Universe

Relativistic Heavy Ion Collisions

- Heavy-ion collisions (CuCu, InIn, AuAu or PbPb … etc) with high energy

~ 5 TeV @ LHC

Create hot and dense medium



Before collision

freeze out and hadronization

Relativistic Heavy Ion Collisions

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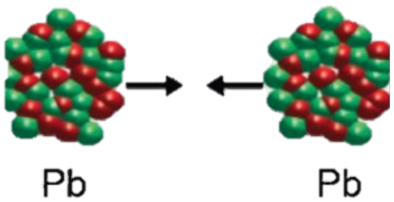
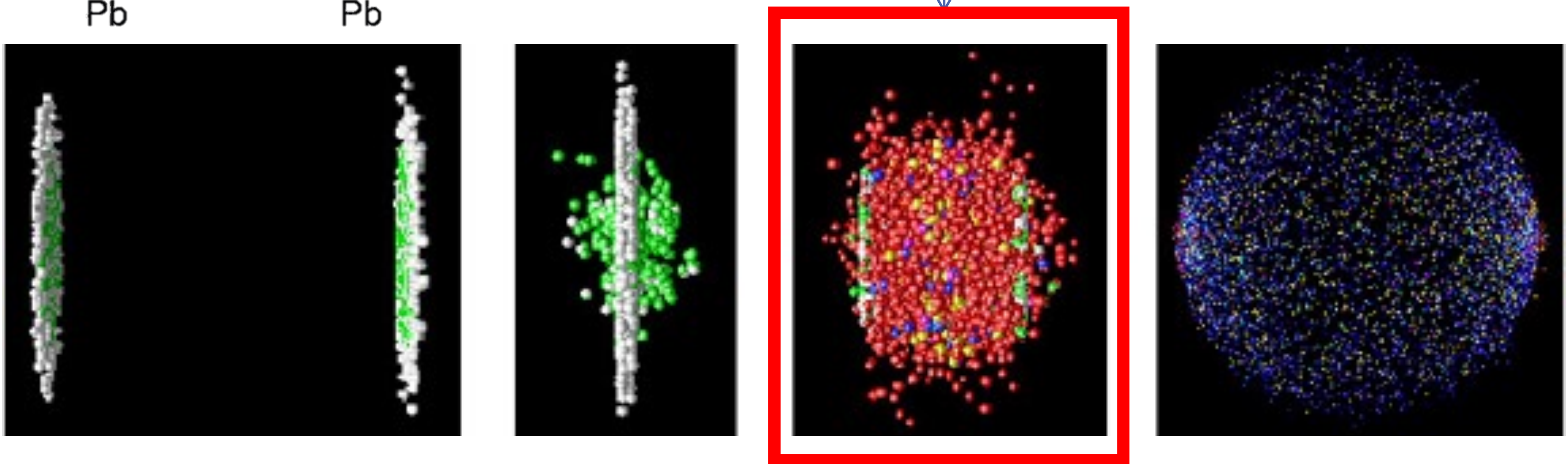


Create hot and dense medium
(Quark-Gluon-Plasma (QGP) state and hydrodynamic expansion)



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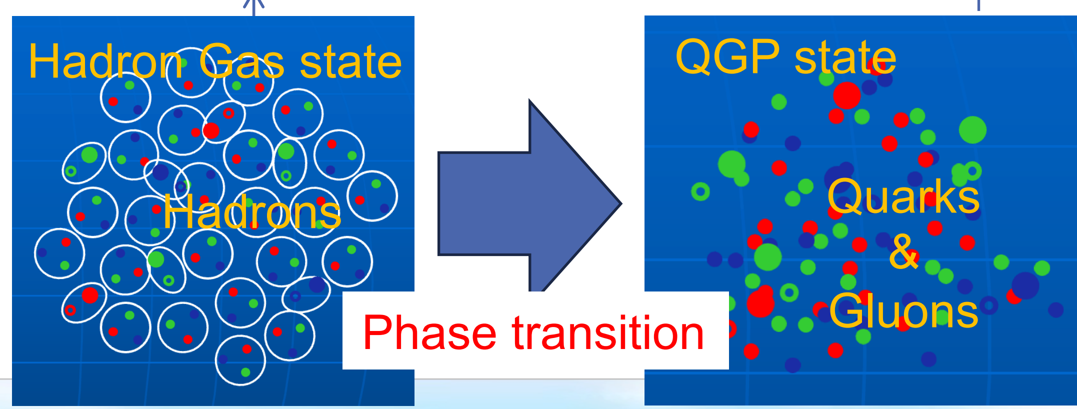
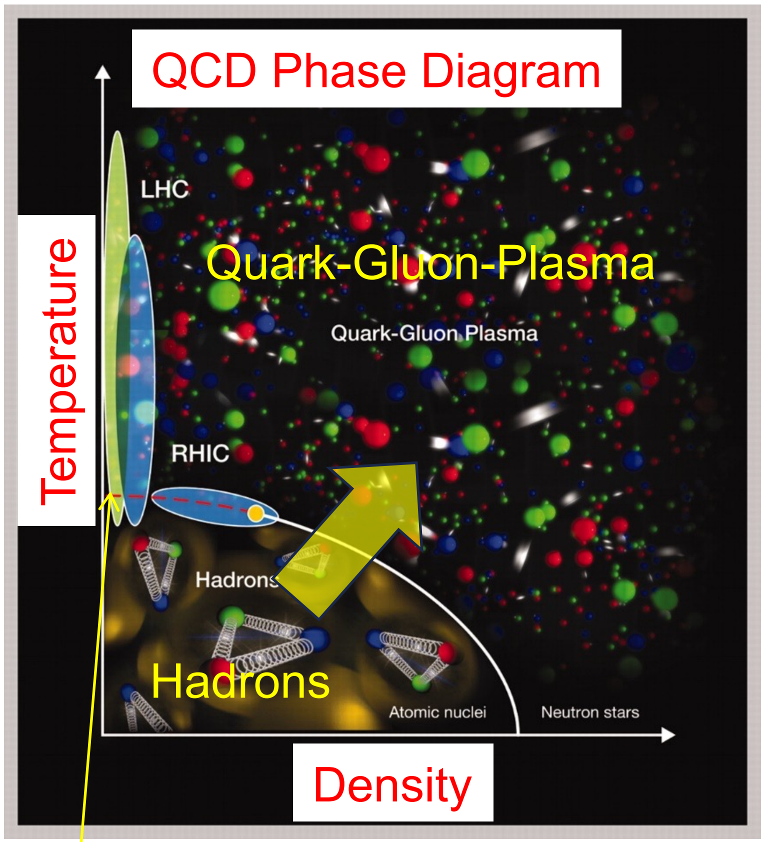


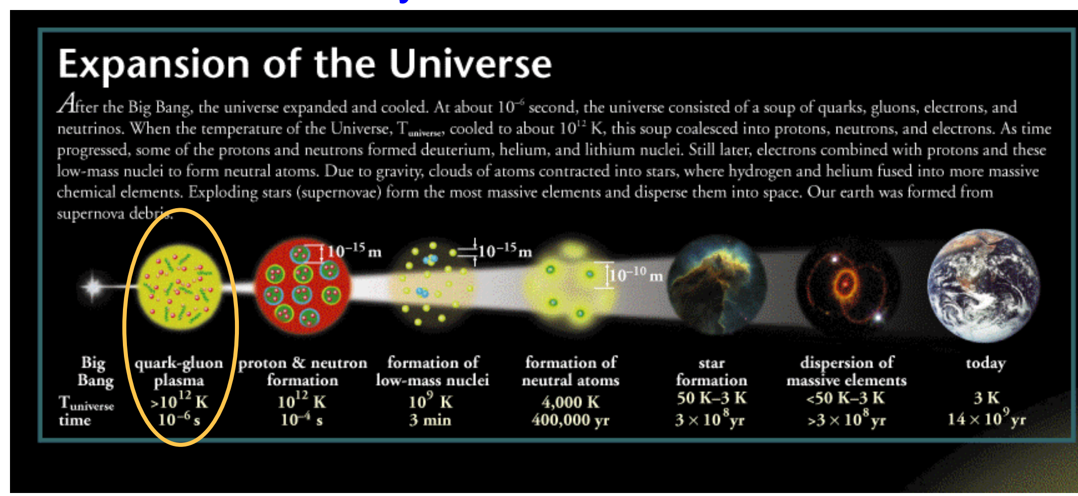
One of Windows on the Universe



T_c (Critical temperature)
: 150~200 MeV(Lattice QCD)

Why is Quark-Gluon-Plasma important ?

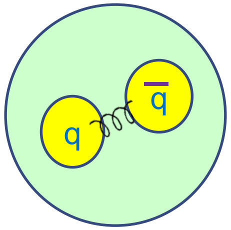
- A phase of Quantum Chromodynamics (QCD)
- Deconfined state of hadrons
- Consist of asymptotically free quarks and gluons
- Exist at extremely high temperature and density
- State of the early Universe for one microsecond



Exploring QGP means exploring the earliest moment of our universe we can achieve

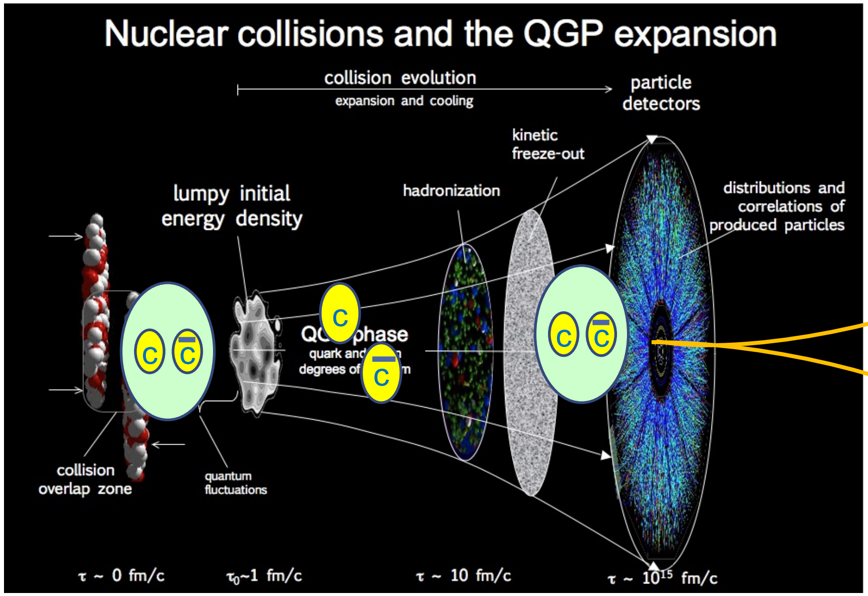
Quarkonia in Heavy ion Collisions

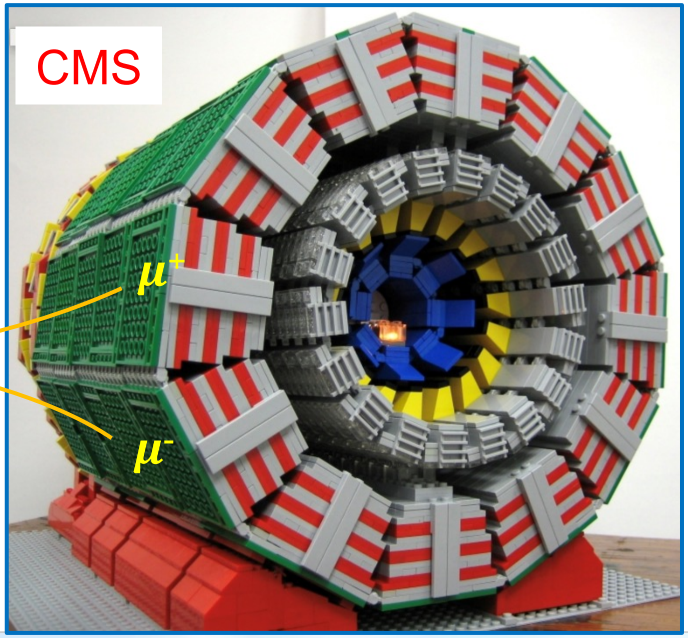
- Quarkonia : Excellent Probes for the Quark-Gluon-Plasma
  - Heavy quark and anti-quark bound states
  - Massive and early production by hard scattering



$$\tau_{formation}(q\bar{q}) \le \tau_{formation}(QGP) < \tau_{life\ time}(QGP) < \tau_{decay\ time}(q\bar{q})$$

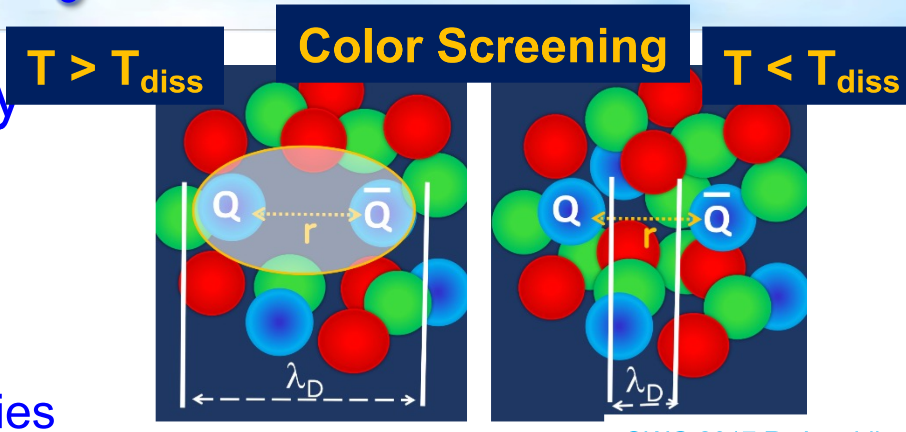
➠ expected to experience whole QGP evolution



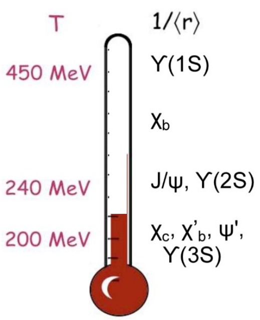


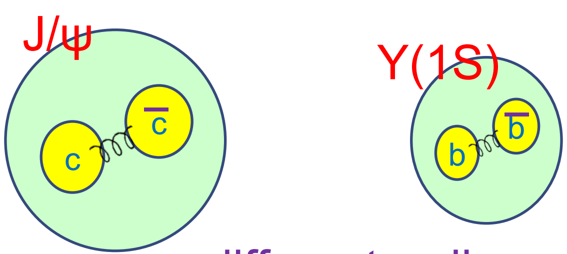
Quarkonia in Heavy ion Collisions

- Quarkonia productions in heavy ion collisions
  - **Suppression**
    - ✓ **Color Screening** : melting depending on different temperatures and binding energies (**Sequential Melting**)
    - ✓ **Parton energy loss** in medium
    - ✓ **Cold Nuclear Matter (CNM) Effects** : Nuclear PDFs, multiple scattering, absorption .. etc
  - **Enhancement**
    - ✓ **Statistical Regeneration (recombination)**



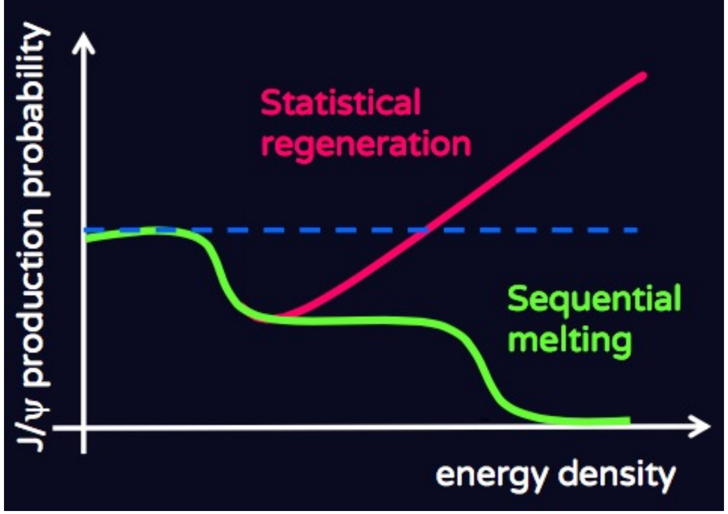
QWG 2017 R. Arnaldi





different radius

Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 2.76TeV
N_{ccbar}/event	~0.2	~10	~85



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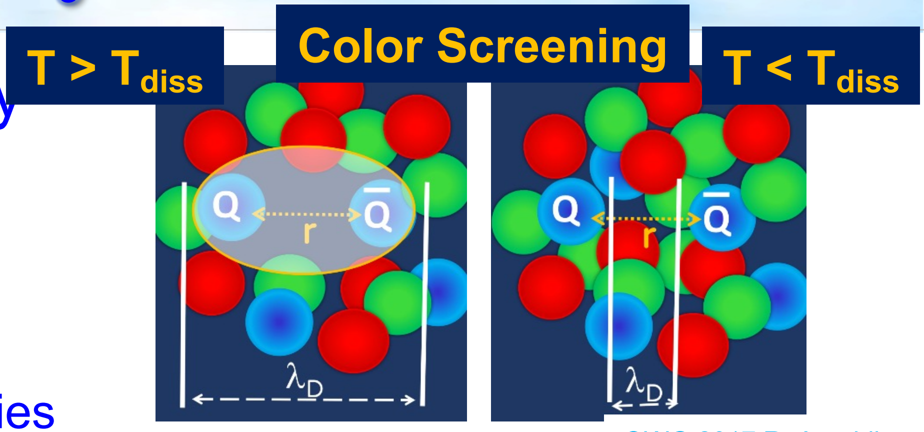

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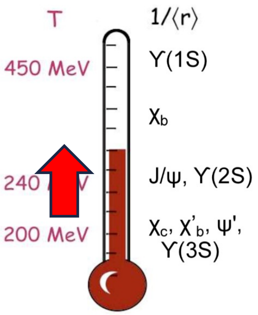

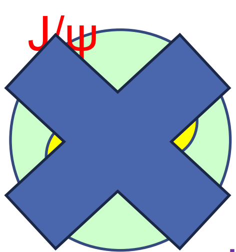

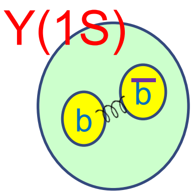

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  - **Enhancement**
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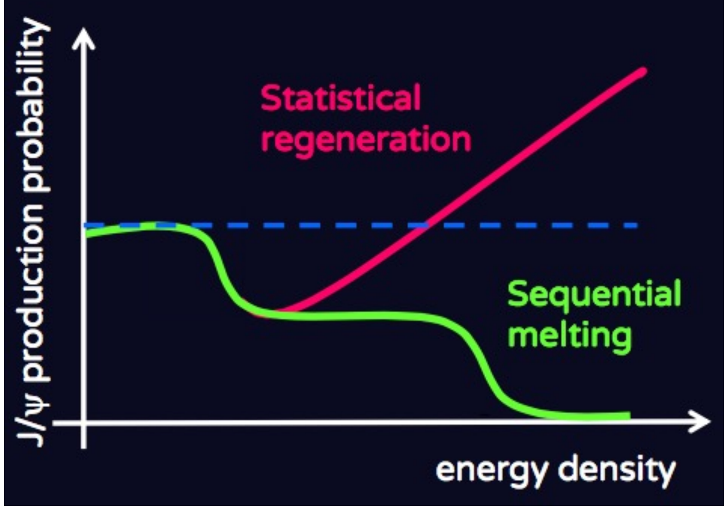
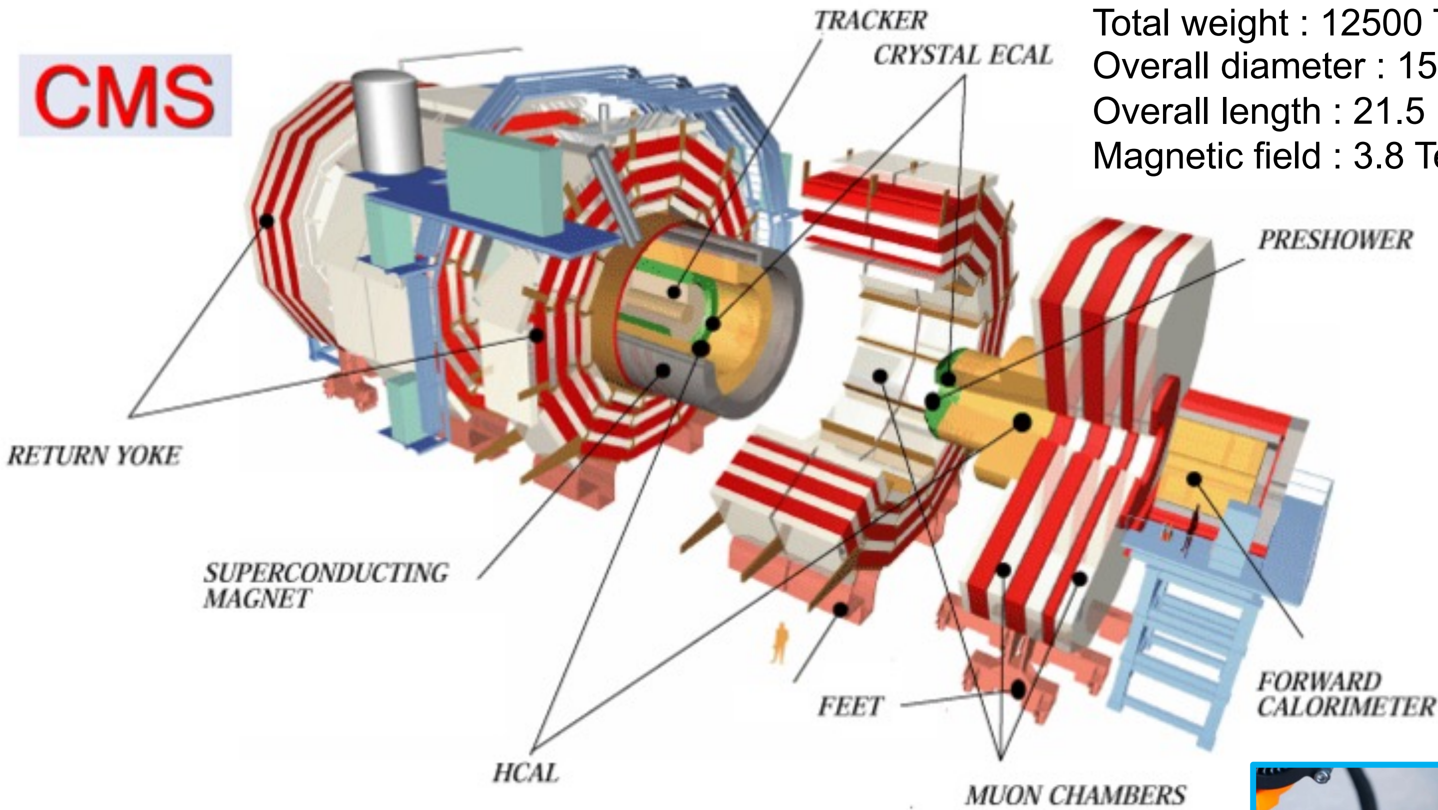
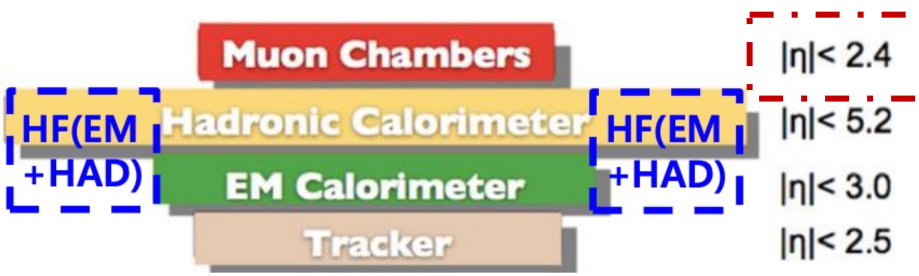
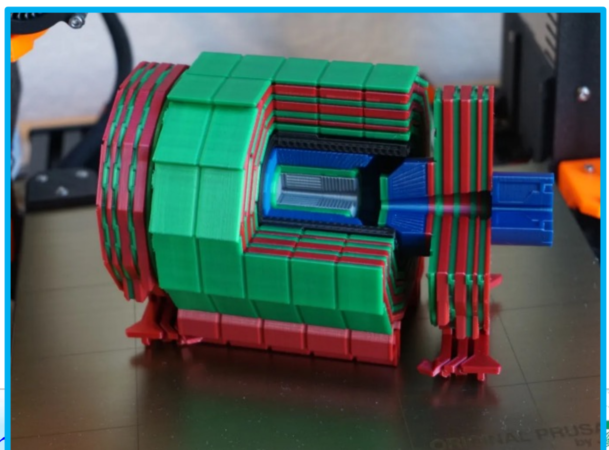


CMS Detector

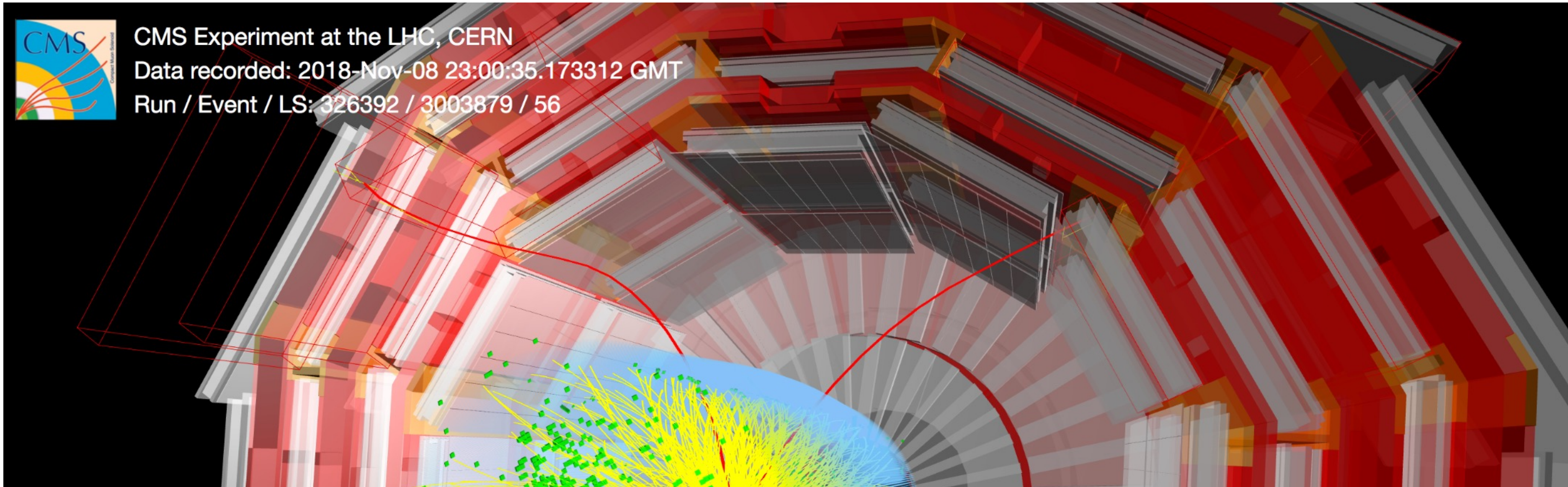
Total weight : 12500 T
Overall diameter : 15 m
Overall length : 21.5 m
Magnetic field : 3.8 Tesla

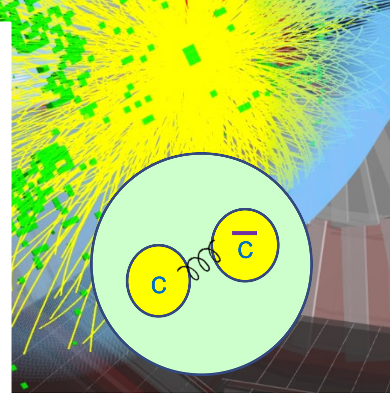


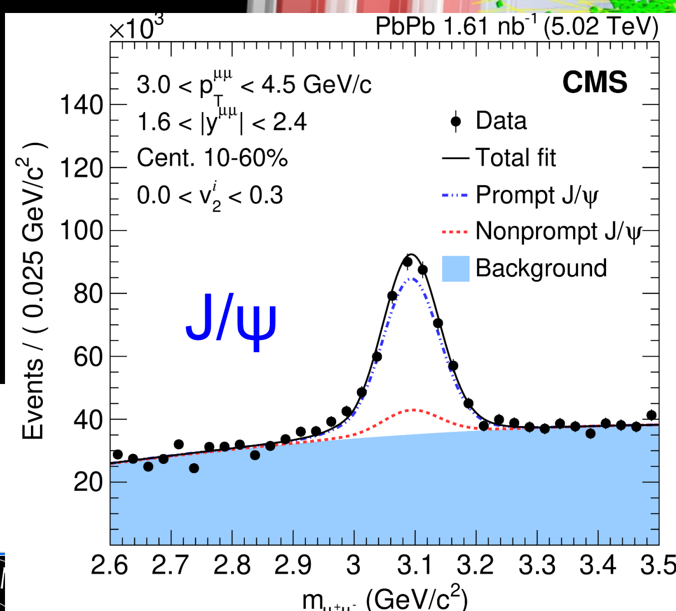


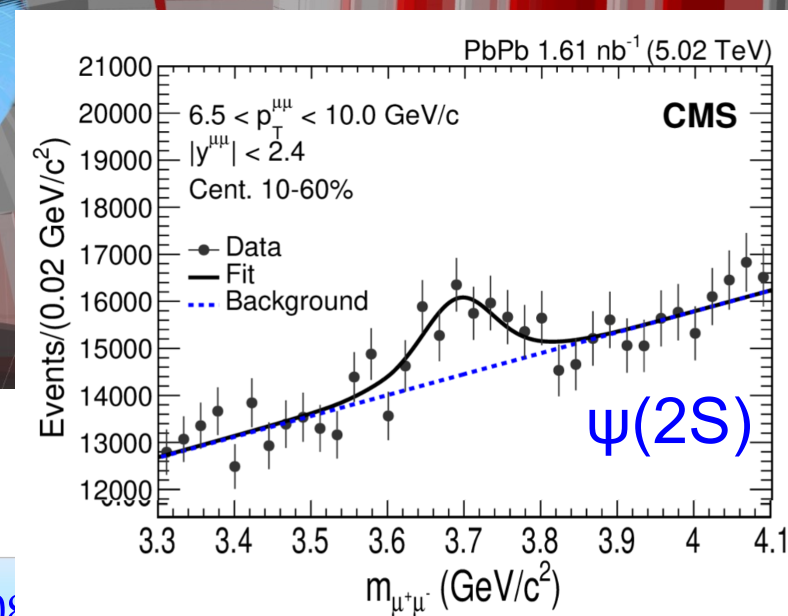


Charmonia in pp & pA & AA



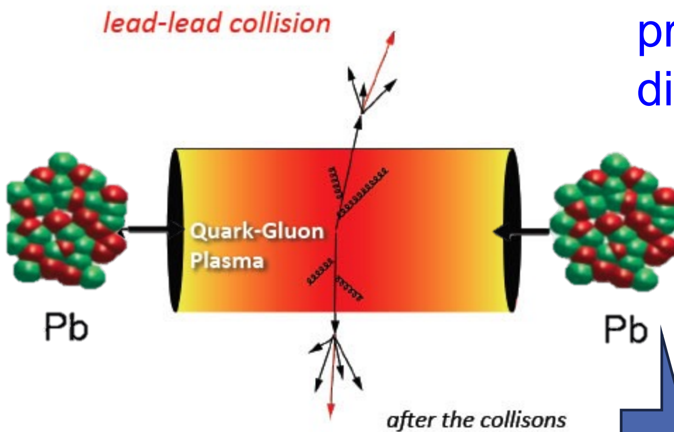




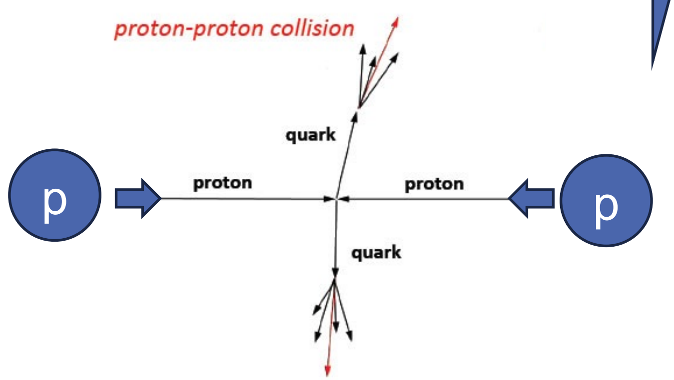


Nuclear Modification Factor

Main question : How much the particles produced in pp and PbPb collisions are different ?



$R_{AA}=$



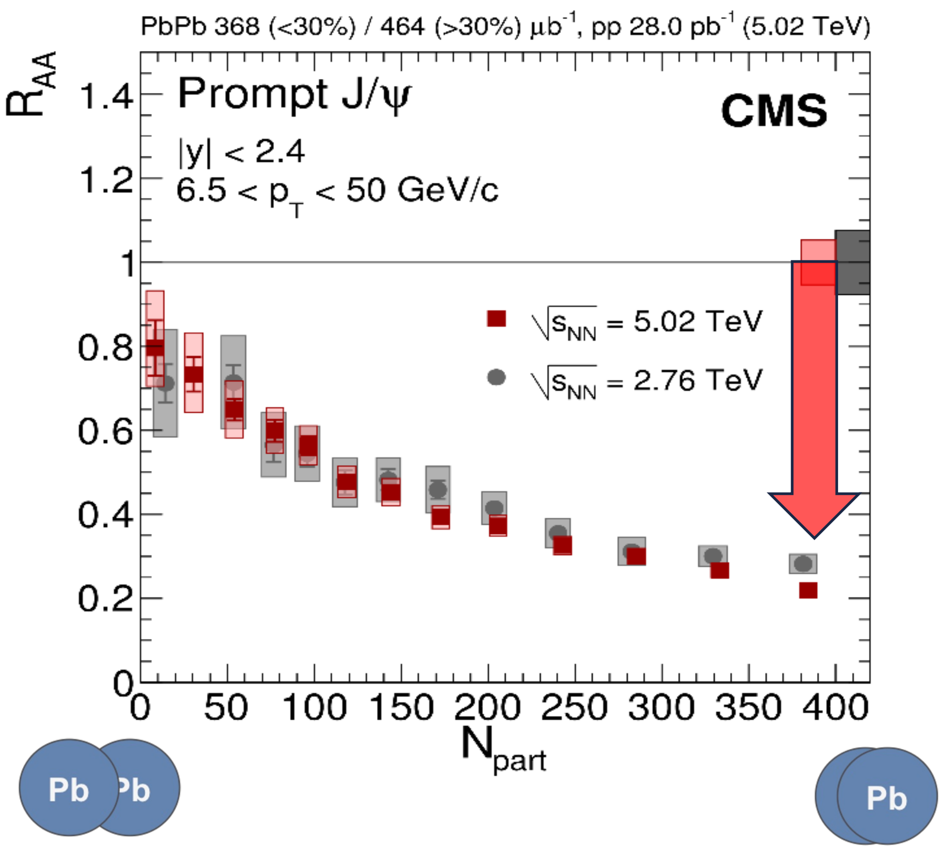
$$R_{AA} = \frac{Yield_{AA}/\langle N_{Coll}\rangle}{Yield_{pp}}$$

$\langle N_{Coll}\rangle$ = number of binary collisions

$R_{AA} > 1$: enhancement
$R_{AA} = 1$: same as pp
$R_{AA} < 1$: suppression

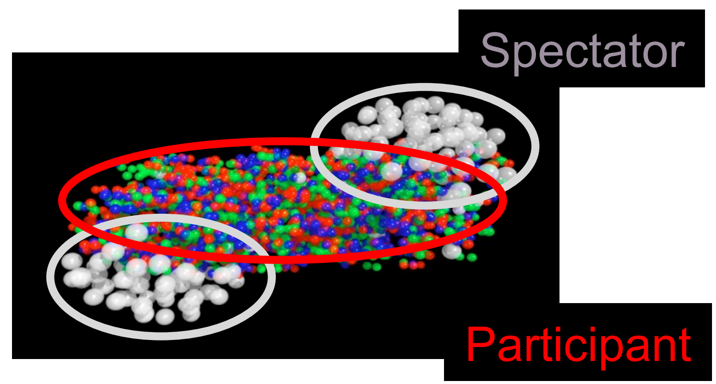
R_{AA} of Prompt J/ψ

EPJC 78 (2018) 509



$$R_{AA} = \frac{\mathrm{Yield}_{AA} / \langle N_{Coll} \rangle}{\mathrm{Yield}_{pp}}$$

N_{Coll} = number of binary collisions



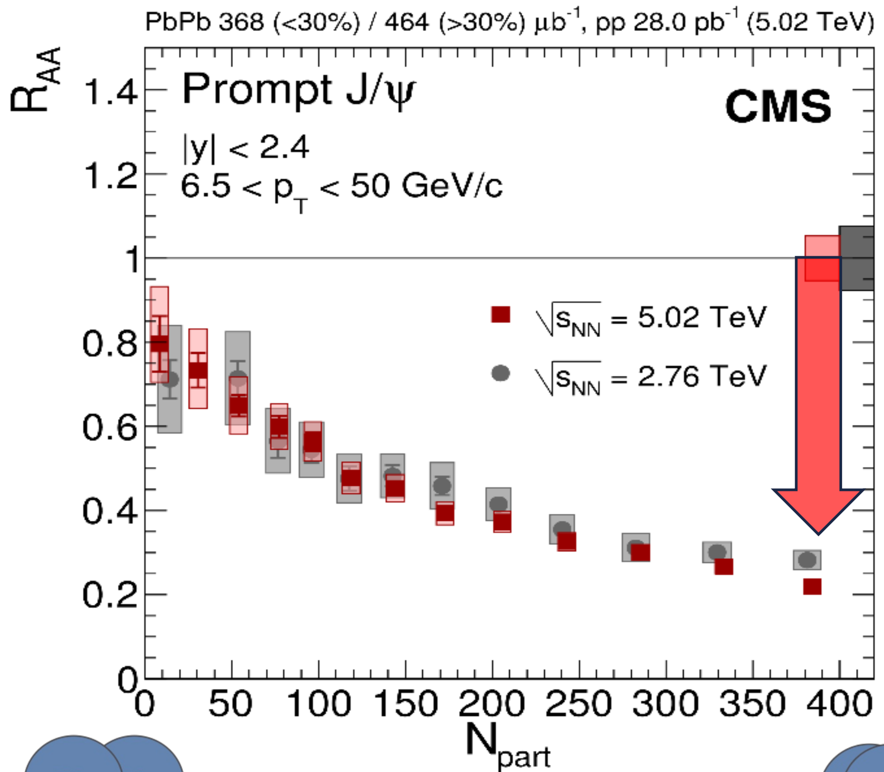
N_{part} = number of participants

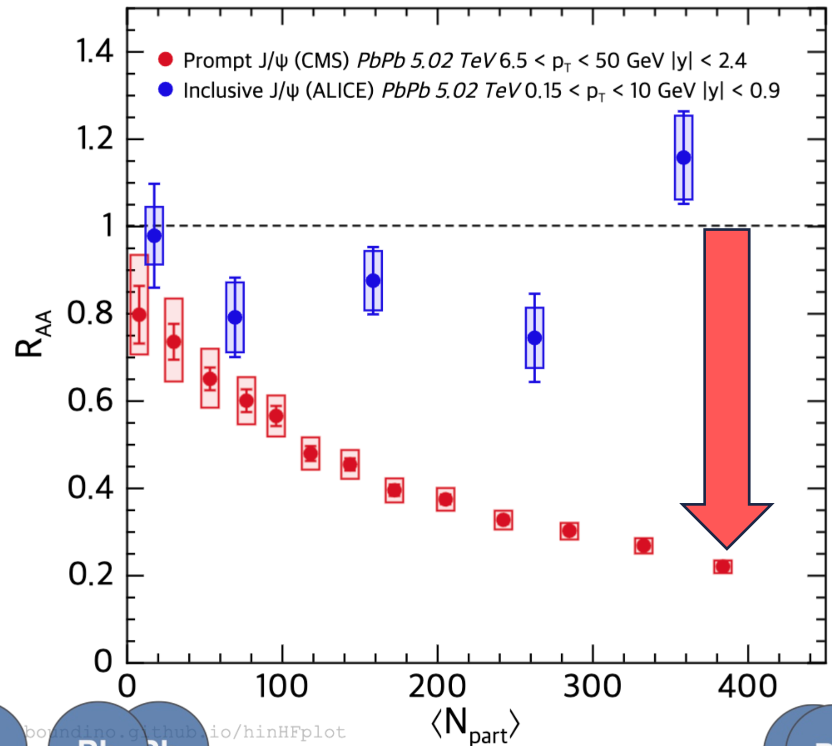
- Gradual suppression depending on number of participants :
  - Observed the significant disappearance of prompt J/ψ on larger N_{part}
  - Slightly more suppressed in higher collision energy

Comparison with ALICE

EPJC 78 (2018) 509

PLB 805 (2020) 135434

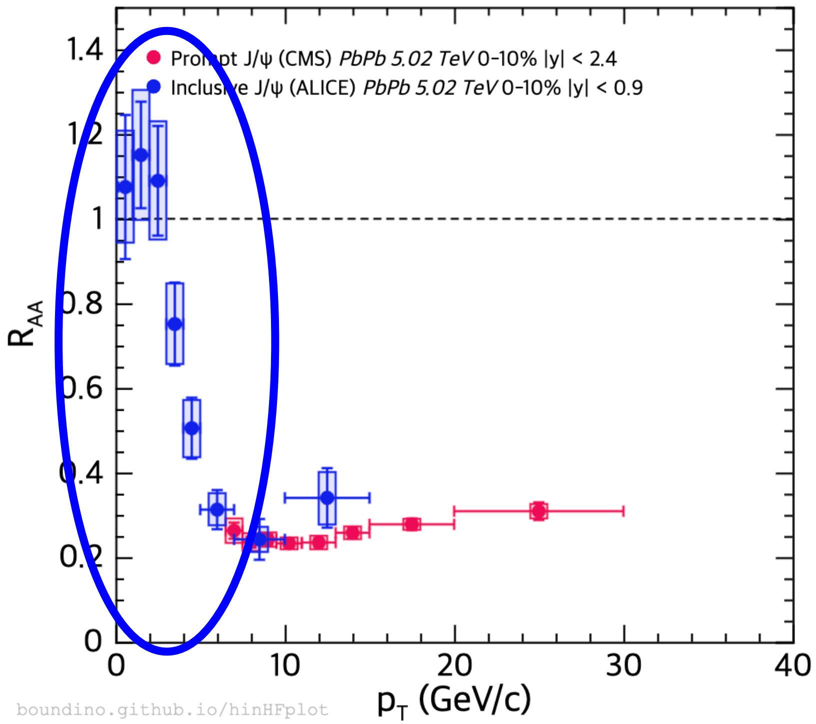




- But ALICE observed the less suppression than CMS
  - Enhancement of J/ψ : where comes from?

Comparison with ALICE

EPJC 78 (2018) 509
arXiv:2303.13361



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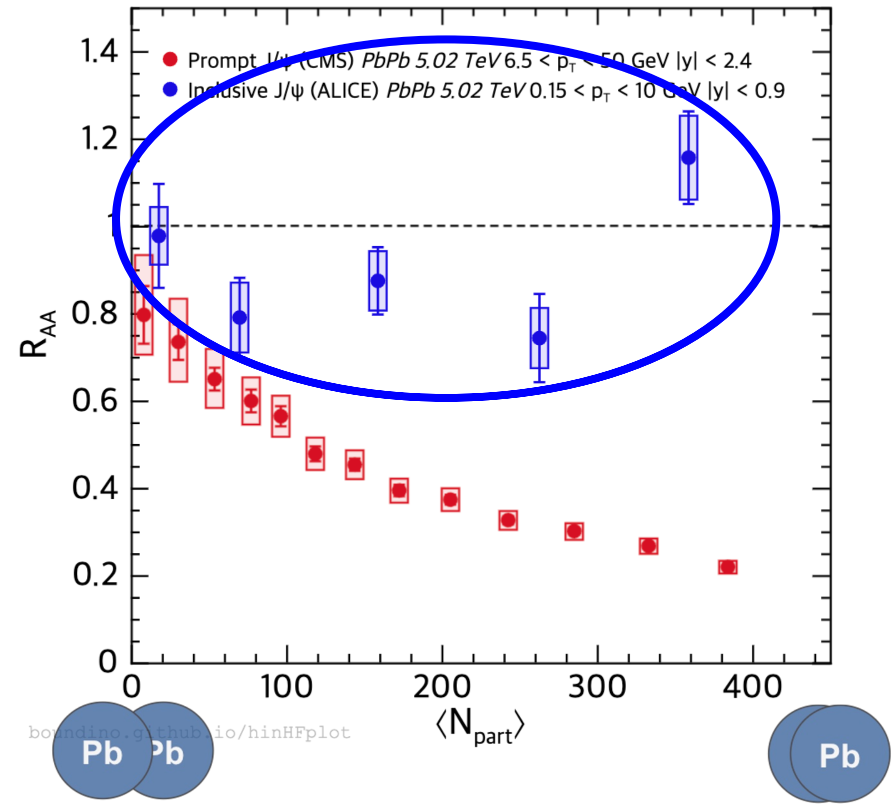
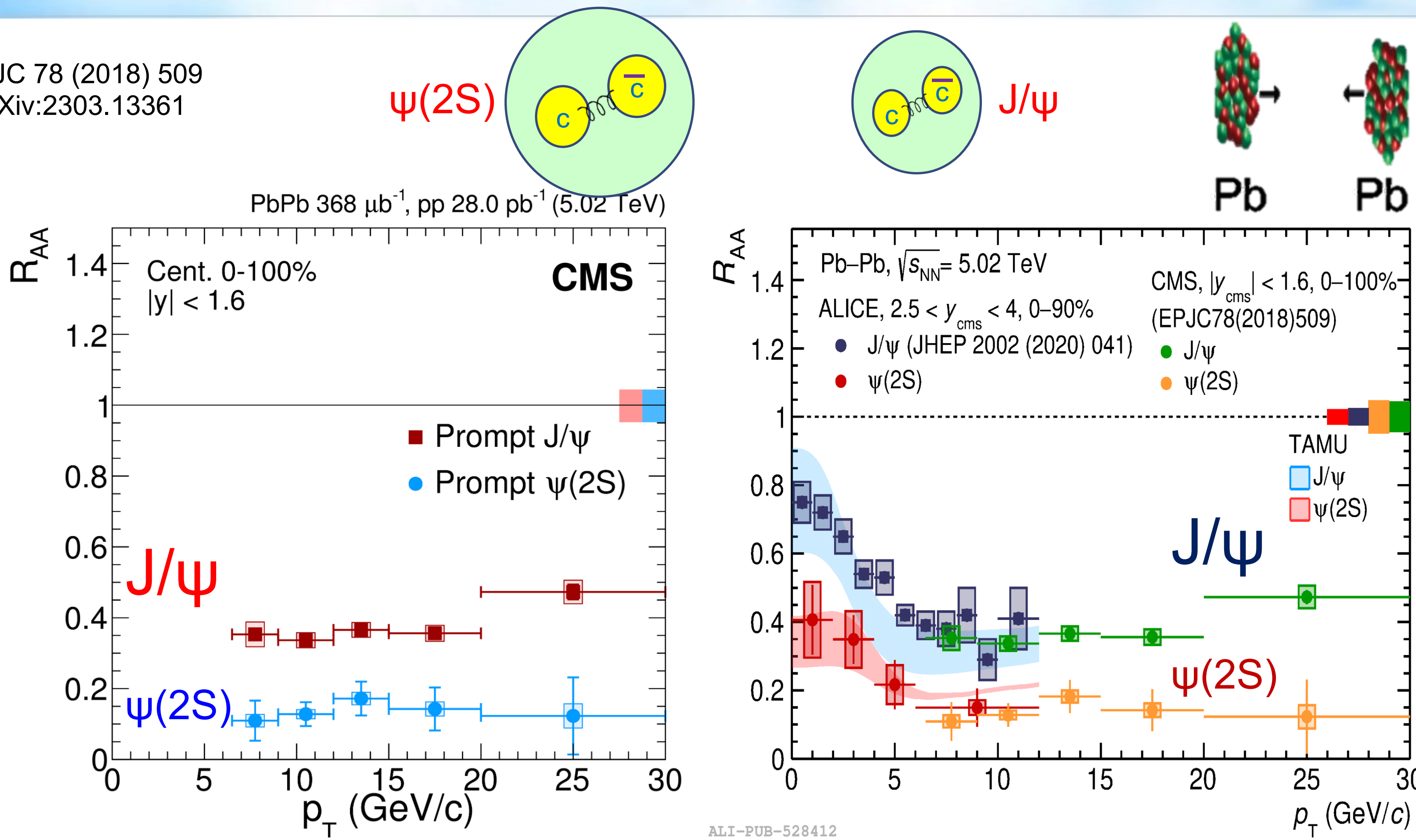


- But ALICE observed the less suppression than CMS
  - Enhancement of J/ψ : mainly comes from low p_T region >> statistical regeneration effect is dominant for low p_T J/ψ

Sequential Melting in Charmonia

EPJC 78 (2018) 509
arXiv:2303.13361



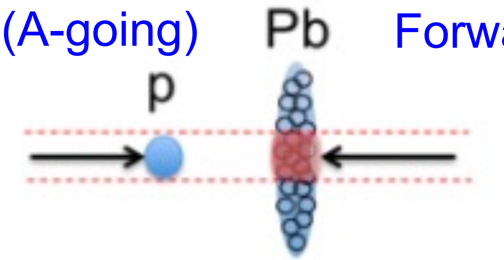
- Clear sequential suppressions are observed in CMS and ALICE as expected.
- Increasing toward low p_T region in ALICE supports the statistical regeneration scenario.

Charmonia in pA

Is the suppression caused by pure QGP effects?

Charmonia in pA

Backward (A-going) Forward (p-going)



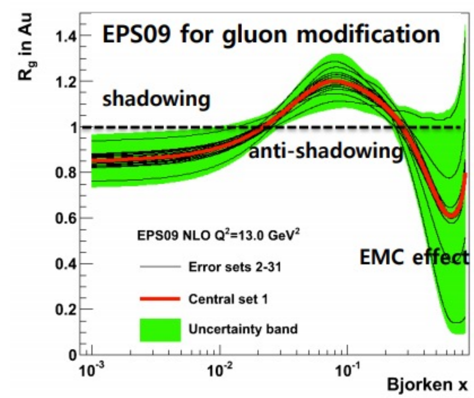
$$R_{FB} = \frac{\text{Yield at Forward}}{\text{Yield at Backward}}$$

$$R_{pPb} = \frac{1}{208}\frac{\sigma^{p+Pb}}{\sigma^{pp}}$$

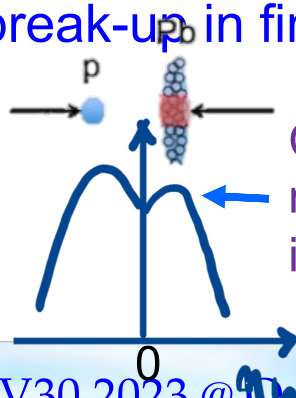
Is the suppression caused by pure QGP effects?
There are several nuclear effects.

Cold Nuclear Matter (CNM) Effect

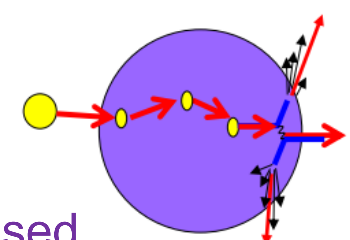
- ✓ Different PDF (nPDF) in nuclear matter
- ✓ Multiple scattering and energy loss
- ✓ Transverse momentum broadening
- ✓ co-mover break-up in final state

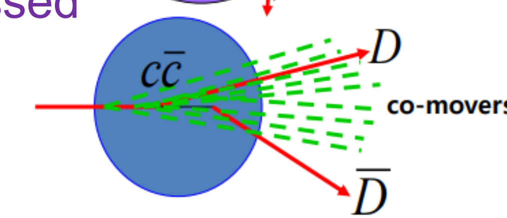


Expectations



CNM effects can make particles suppressed in forward

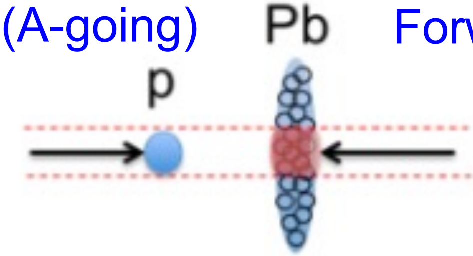




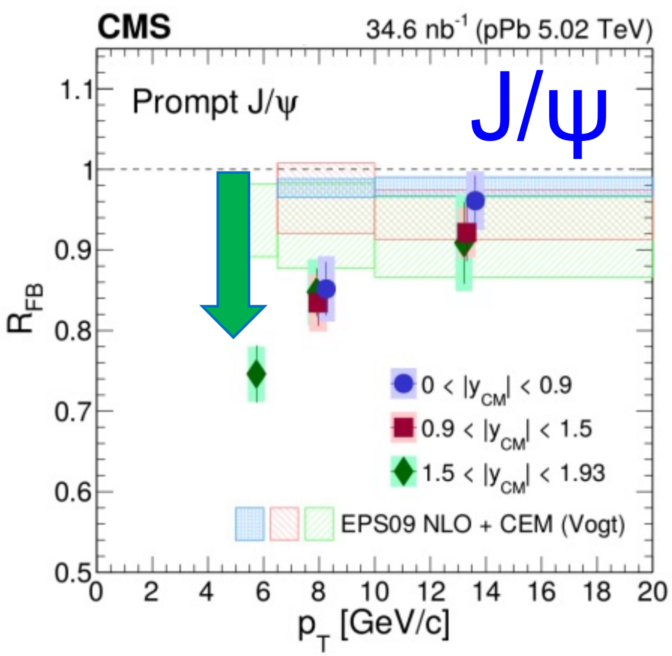
S.Lim HP2020

Charmonia in pA

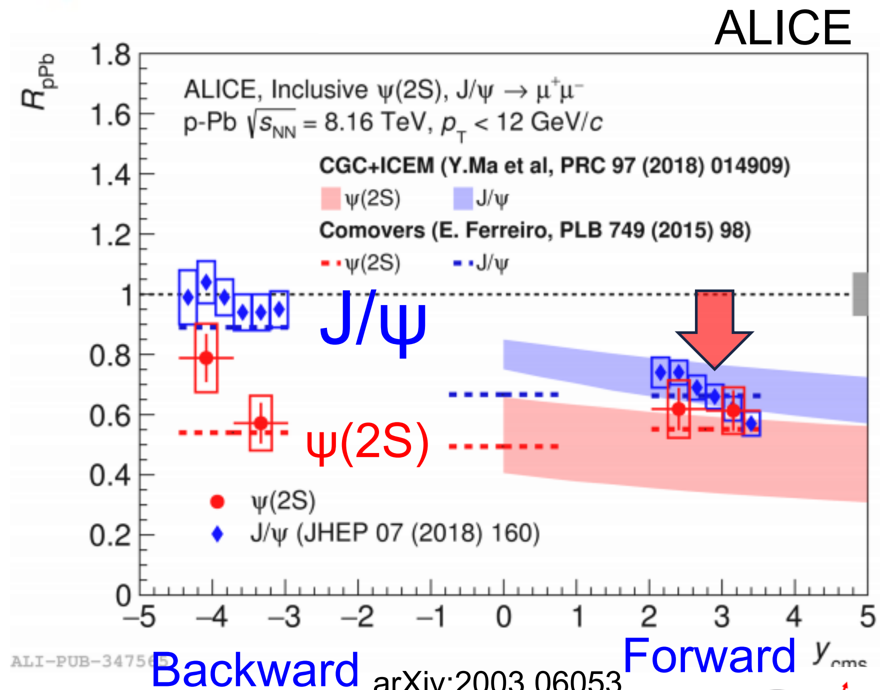
$$R_{FB} = \frac{\text{Yield at Forward}}{\text{Yield at Backward}}$$



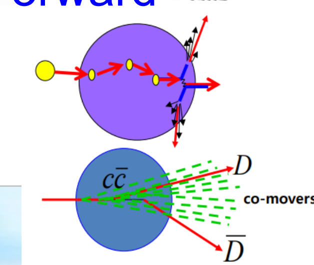
$$R_{\rm pPb} = \frac{1}{208}\frac{\sigma^{p+\rm Pb}}{\sigma^{pp}}$$



EPJC 77 (2017) 269

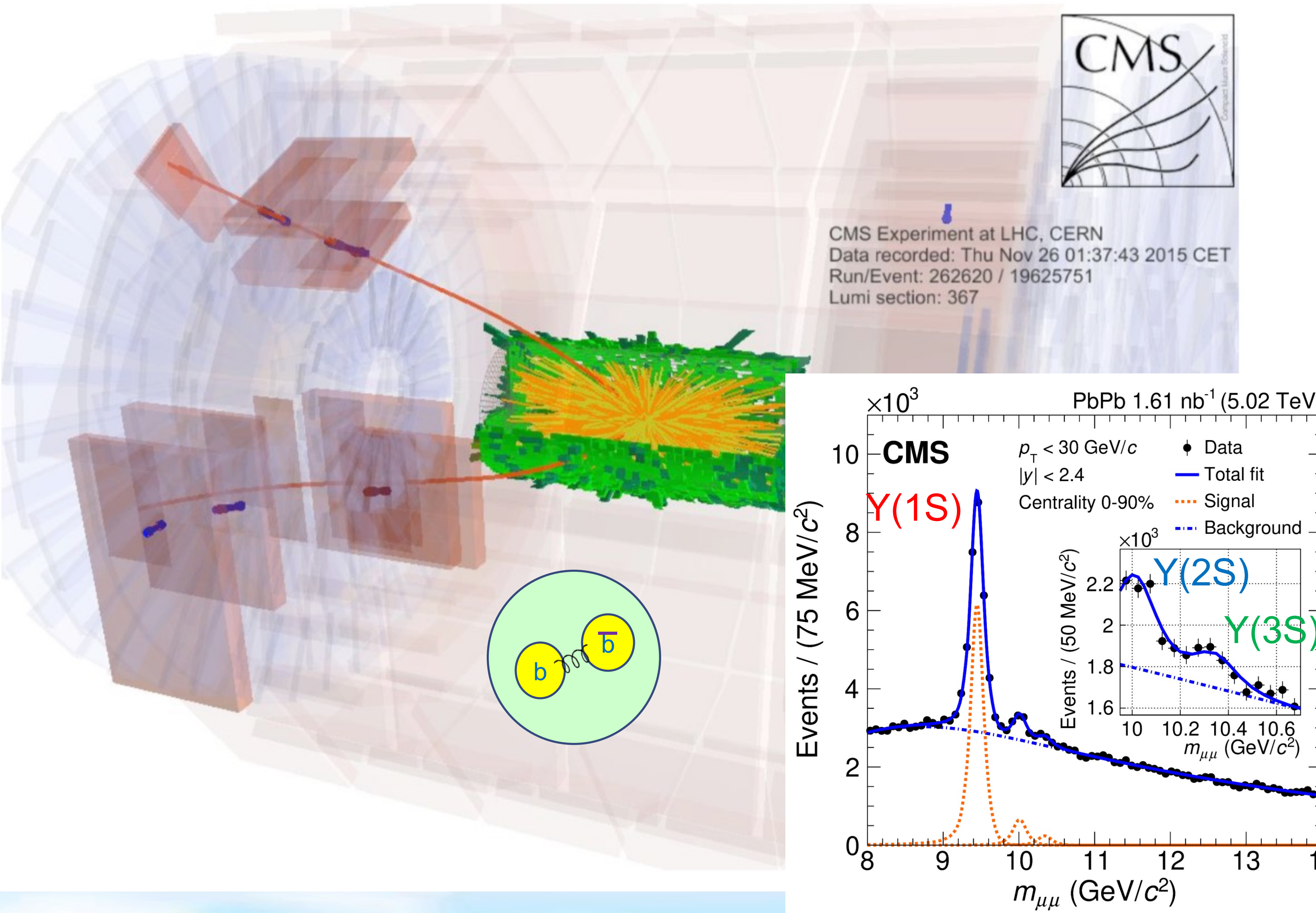


arXiv:2003.06053



- nPDF models describes data in forward.
- But don’t describe the suppression trend well in low p_T region.
- Comover breakup model calculations look better agreements.

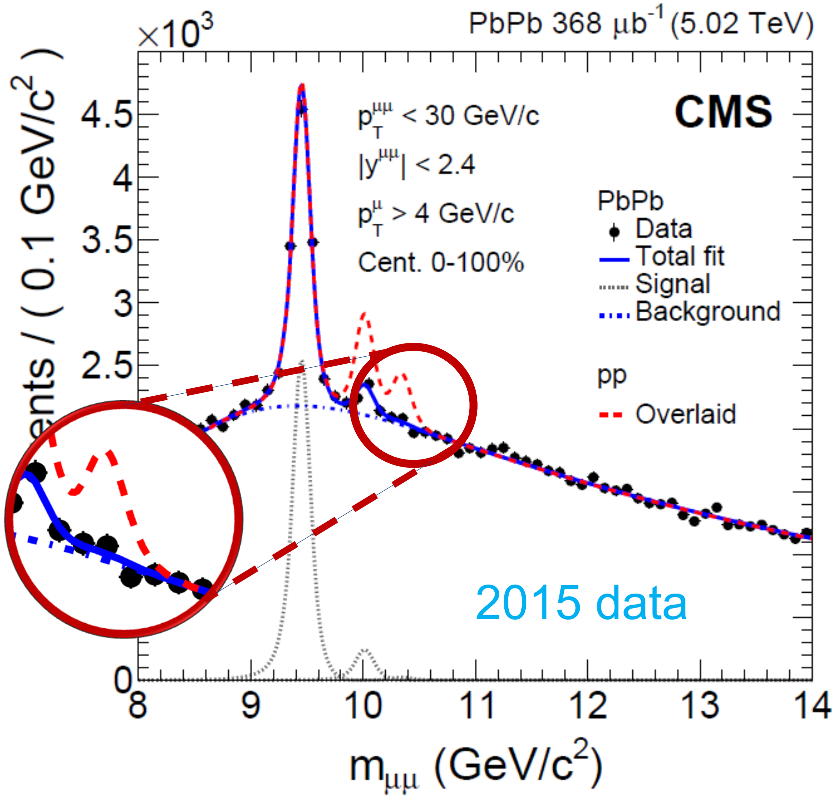
Bottomonia in PbPb

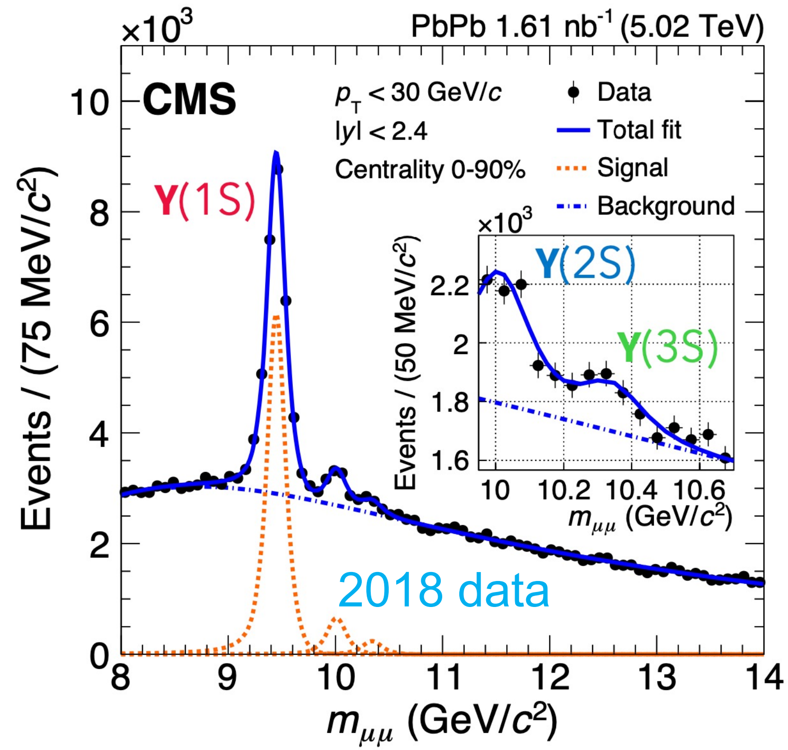


First observation of Υ(3S) in AA

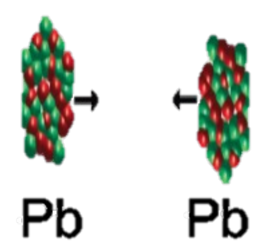
arXiv:2303.17026

Run II 2018 data 1.61 nb^{-1}





- 4 times larger statistics (2018 PbPb data)
- First observation of Υ(3S) in AA collisions (> 5 σ !!!)
- BDT technique helps to get clear signal from background.



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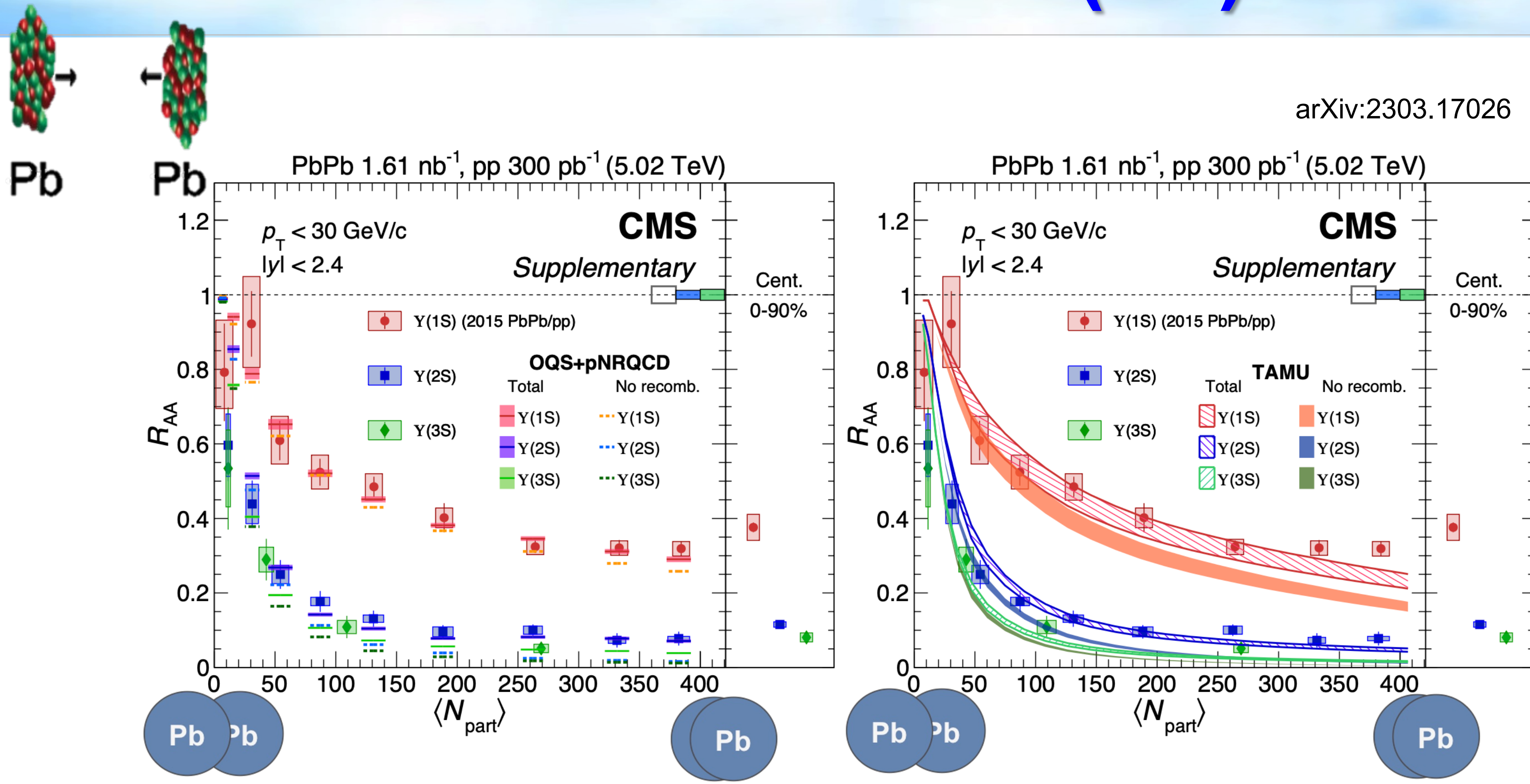
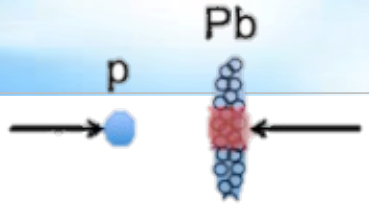
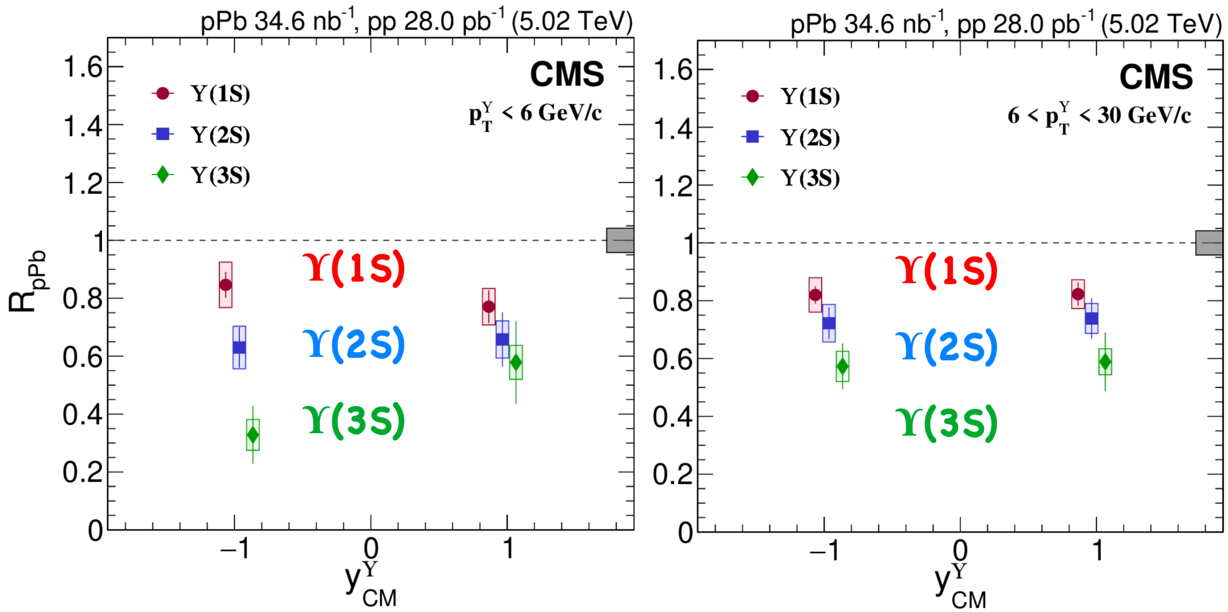


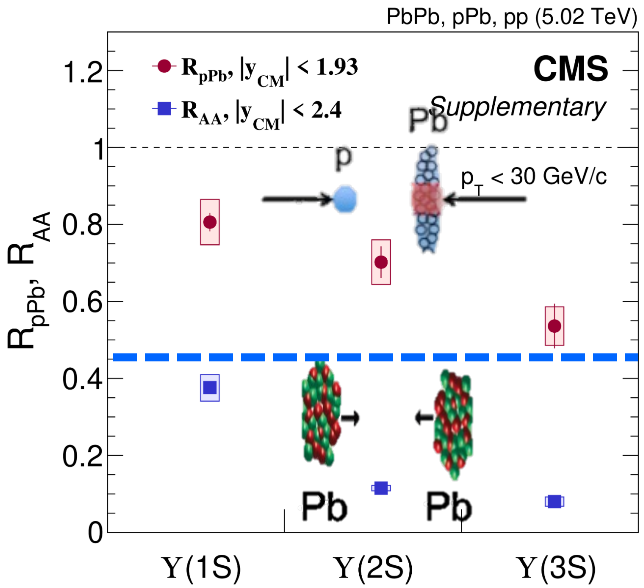
- Sequential melting prediction describe well data but slight tension in most central events (theoretical models assuming $T_0 \approx 600$ MeV).
- Recombination effects of bottomonia are not negligible.

Botomonia in pPb



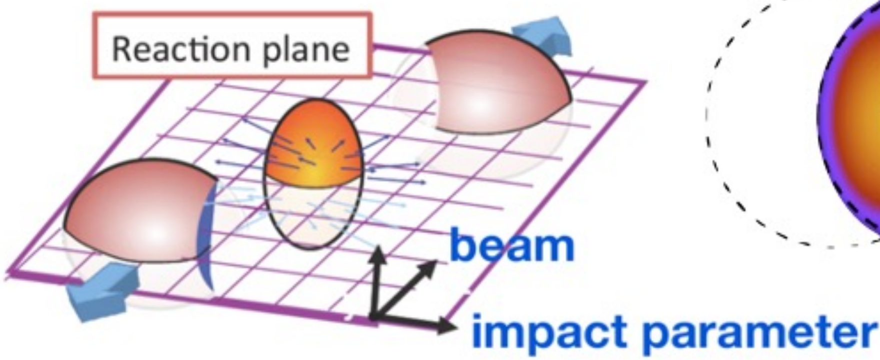
PLB 835 (2022) 137397

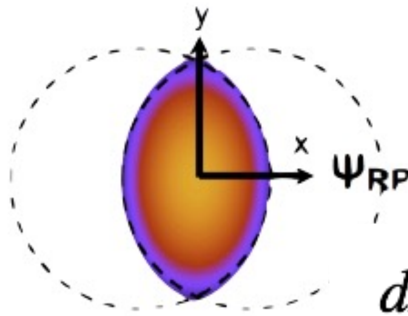


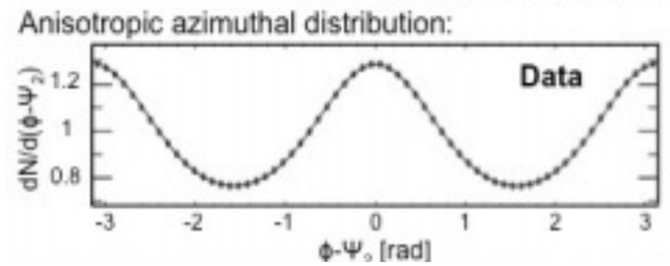


- Sequential suppression also in pPb
- More significant modification in backward for the excited states
- Clear difference between PbPb and pPb in all states

Quarkonia Collective flows



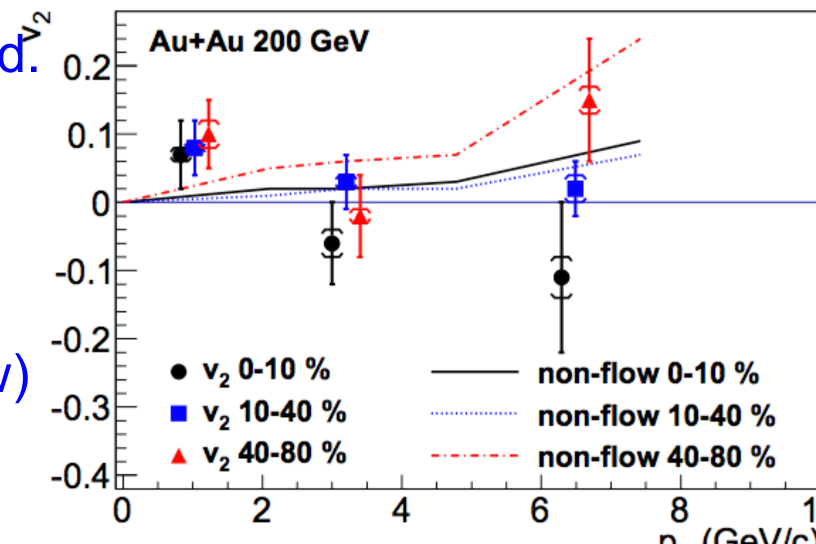




$$\frac{dN}{d\phi} \sim [1 + 2v_2 cos(2(\phi - \psi_2))]$$

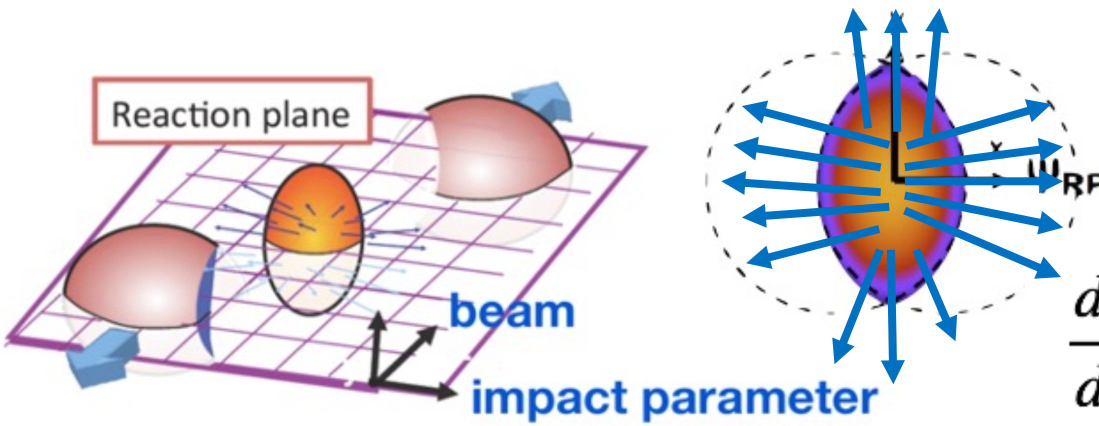
v_2 : Elliptic flow

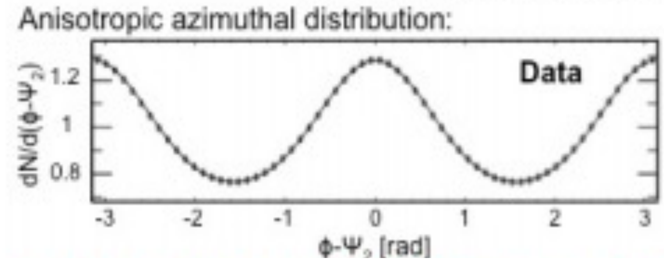
- Pressure difference in collisions can lead.
- Almost zero flow at RHIC
- But significant elliptic flow (v_2) may be expected at LHC energy due to the significant contribution of regenerated J/ψ (inherited charm flow)
  - ✓ Good recombination signal (NPA 834 (2010) 317)



PRL 111 (2013) 052301

Quarkonia Collective flows





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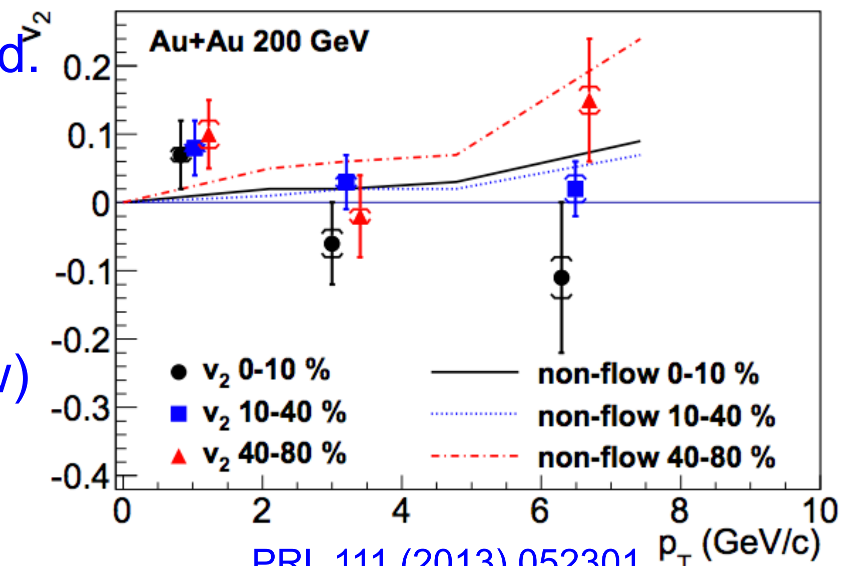
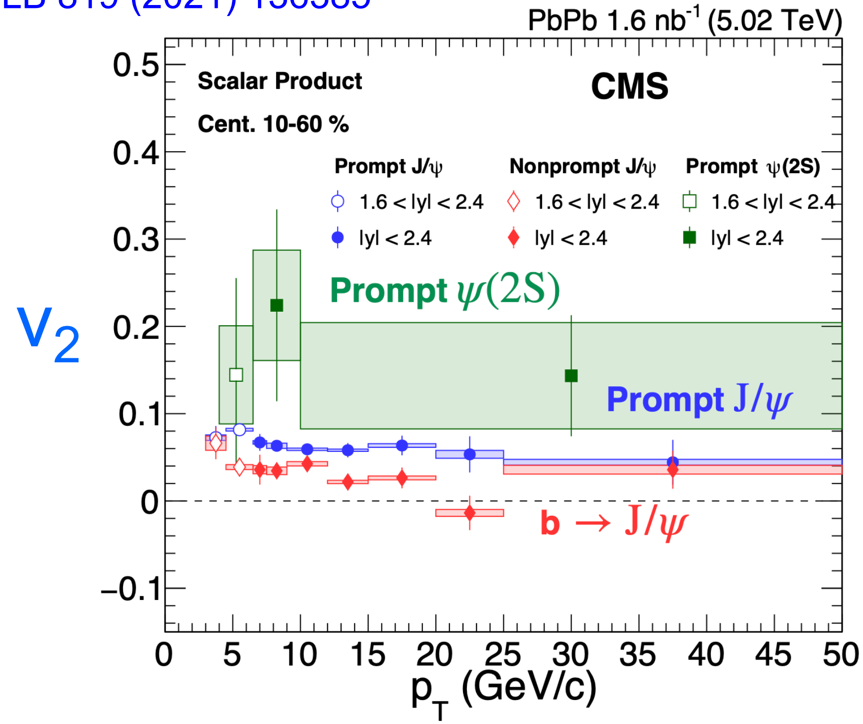


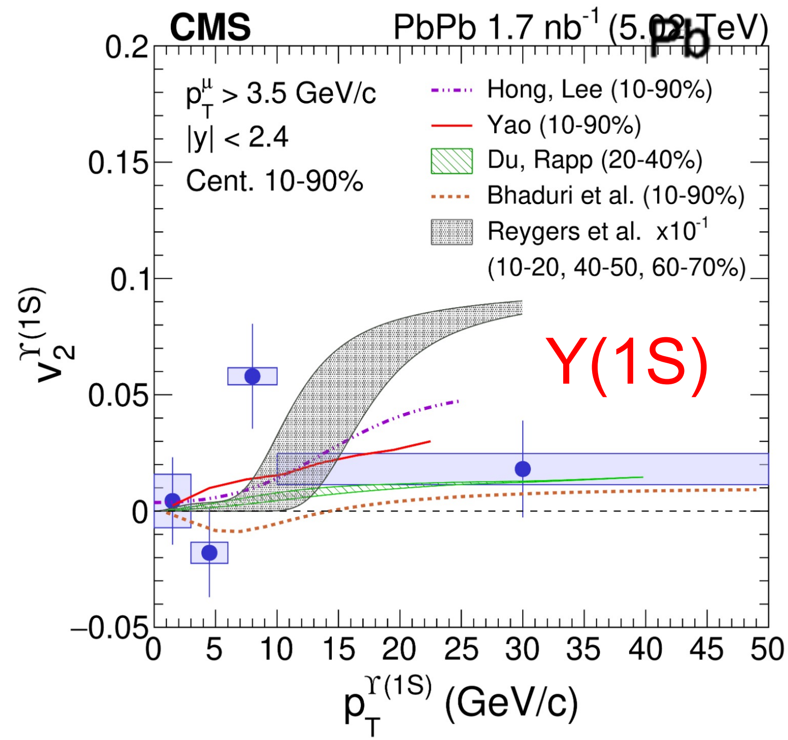
PRL 111 (2013) 052301

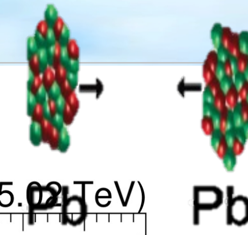
Quarkonia Elliptic Flows

arXiv:2305.16928

PLB 819 (2021) 136385

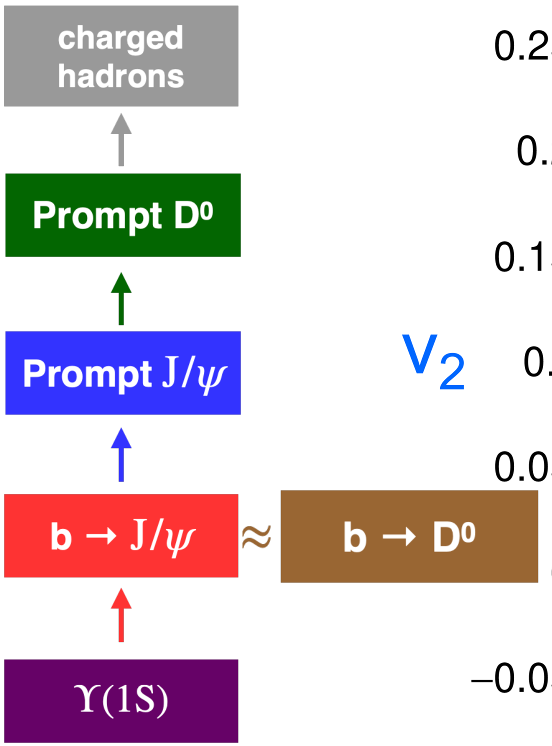


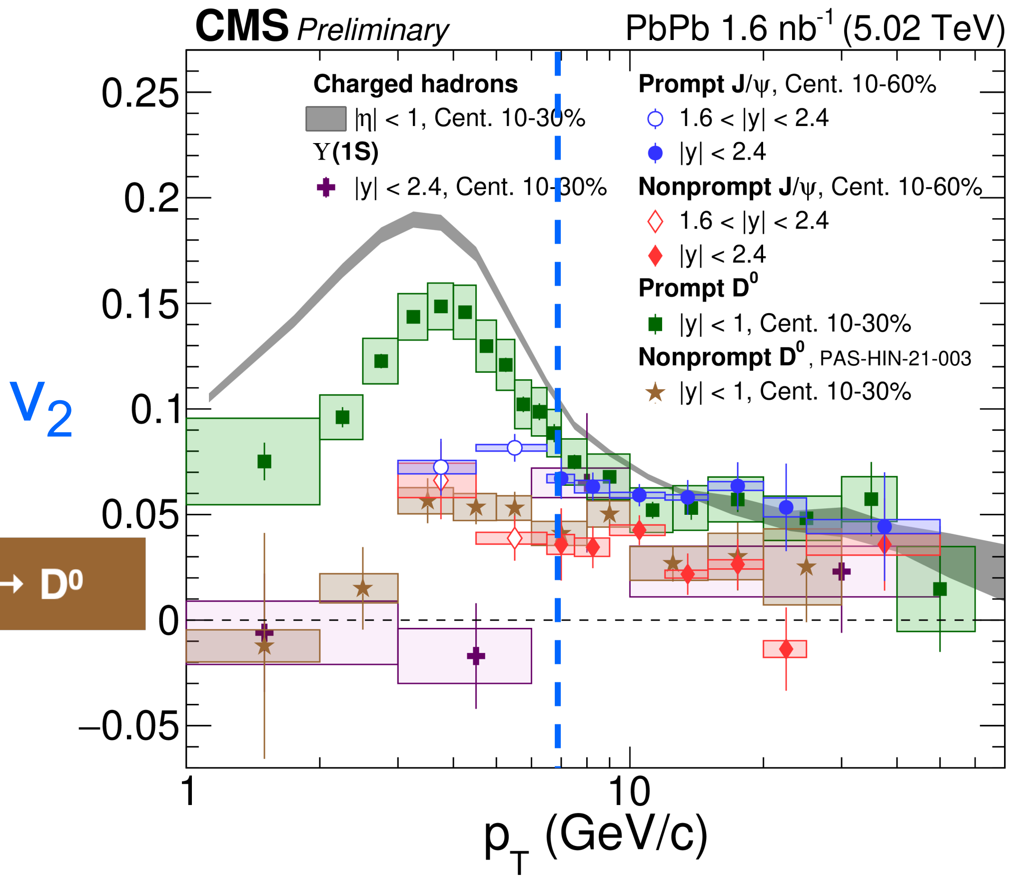




- Measured sizable v_2 of prompt J/ψ and ψ(2S) up to 50 GeV/c
- ψ(2S) v_2 > J/ψ v_2 ? >> hard to make any strong conclusion due to large statistical uncertainties, yet.
- Υ(1S) v_2 is consistent with zero in all p_T

Elliptic Flow Zoo





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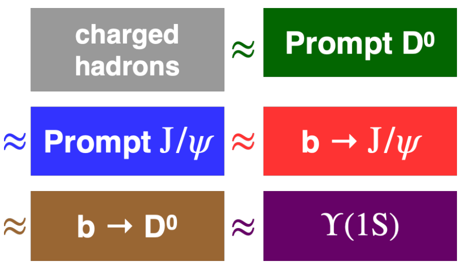
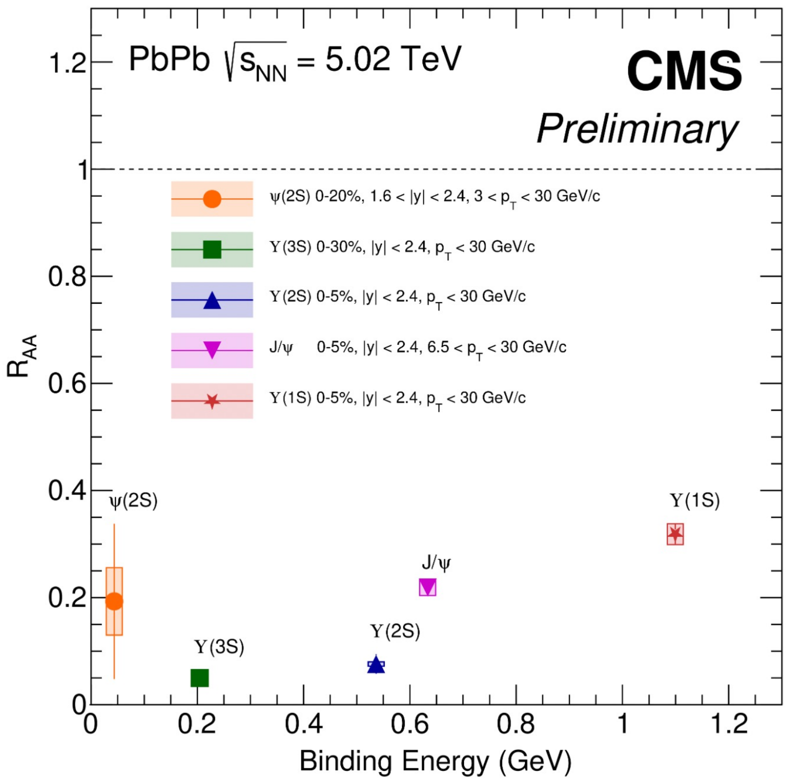
PLB 816 (2021) 136253
PLB 819 (2021) 136385
PLB 776 (2017) 195



- Low p_T : light > charm > beauty (mass ordering), quark flows
- High p_T : universal behavior for all hadron species, pathlength dependence

Summary & Outlook

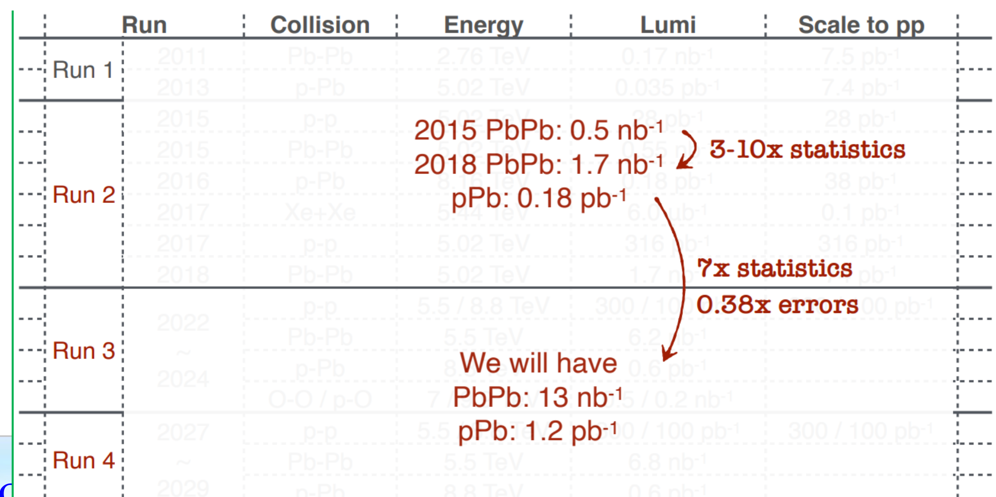


- Clear sequential melting behaviors were observed in quarkonia measurements as increasing binding energy.
- Regeneration effects are dominant in low p_T region.
- Collective behaviors are observed for charm in PbPb and pPb, but not for bottom.

- First measurements of prompt ψ(2S) v_2
- First observation of Υ(3S) clearly

New data coming soon !!!

More interesting results will come.



Thank You Very Much
for your attention !!!