Heavy Ion Quarkonia and Heavy Flavor
CMS + ATLAS Results

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On behalf of
CMS Collaboration
ATLAS Collaboration

The MIT RHIG's work is supported by US DOE-NP

2019 Meeting of the Division of Particles & Fields of APS
July 29 - August 2, Northeastern University, Boston, USA

Heavy Quarks as Hard Probes

- **Open Heavy Flavor**
  - Produced by hard scattering at the early stage
  - Perturbative QCD calculation available
  - Strong interaction with expanding QGP

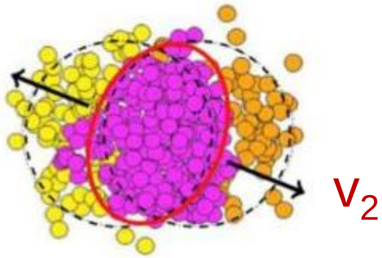
  → In-medium energy loss, collective flow of quarks

  → Key observables: Nuclear Modification Factor R_{AA}

  Azimuthal Anisotropy v_n

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{dN^{AA}/dp_T}{d\sigma^{pp}/dp_T}$$

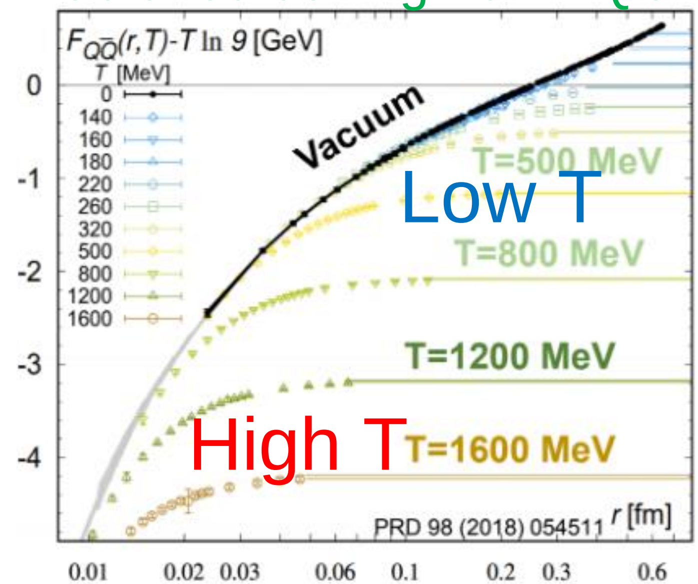
$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} \boxed{2v_n} \cos[n(\phi - \Psi_n)]$$



- **Hidden Heavy Flavor (Quarkonia)**
  - Temperature dependent modification of QCD potential based on LQCD.
  - Various sizes of quarkonia make them melt at different temperatures

  → Key observables: Suppression Pattern

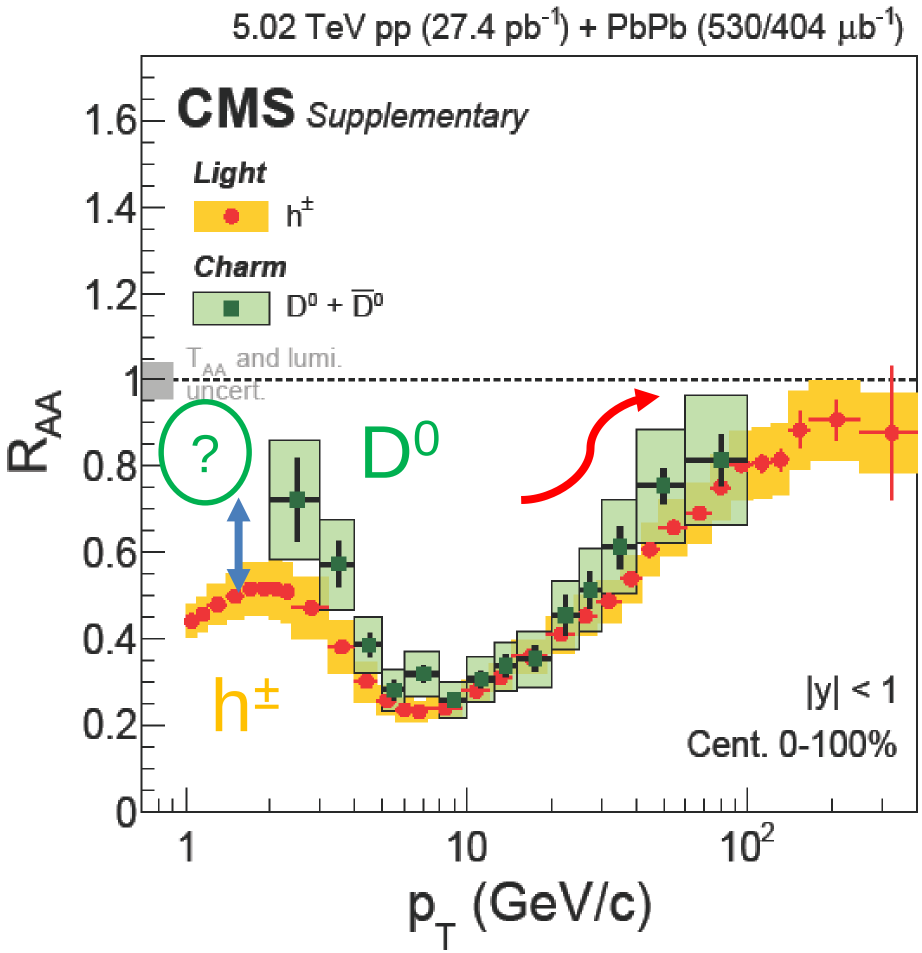
Color screening from LQCD



Flavor Dependent Energy Loss

JHEP 04 (2017) 039
PLB 782 (2018) 474

Charm
vs
Charged hadrons

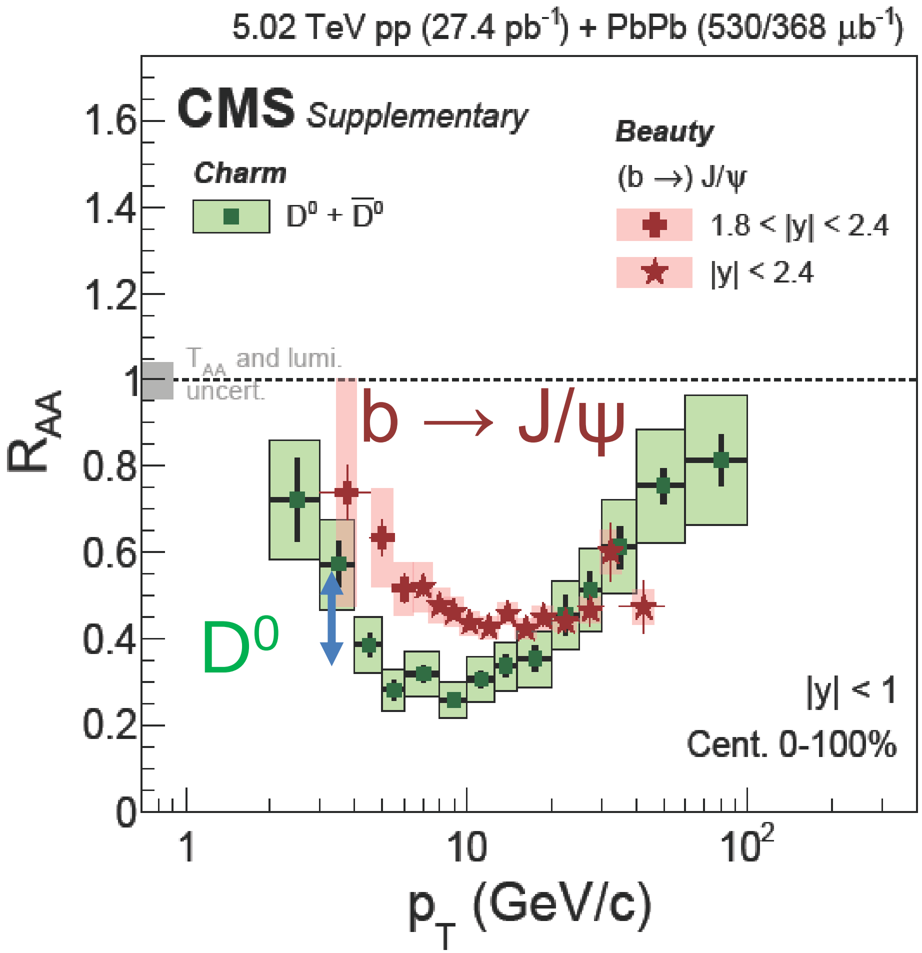


- Prompt D^0 meson is strongly suppressed in PbPb.
- Low p_T : Hint of less suppression of D^0 than charged hadrons
- High p_T : R_{AA} (prompt D^0) ≈ R_{AA} (charged hadrons)

Flavor Dependent Energy Loss

EPJC 78 (2018) 509
PLB 782 (2018) 474

Charm
vs
Beauty (→ J/ψ)

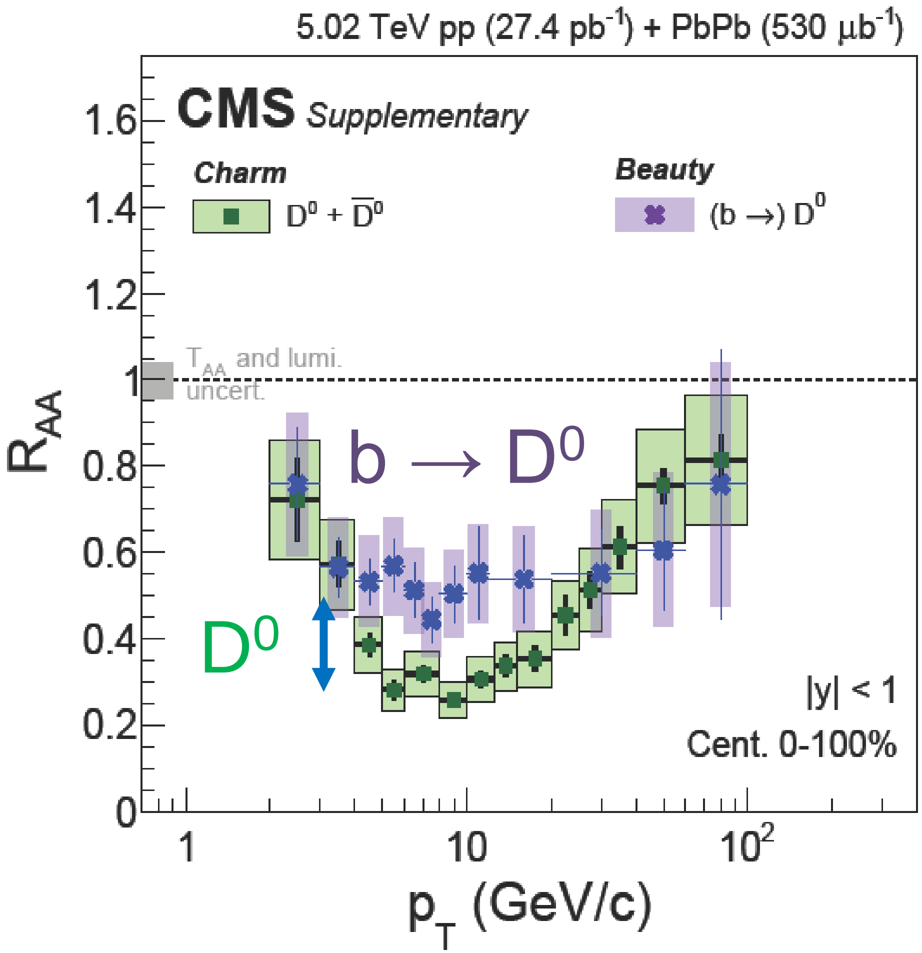


- Low p_T : R_{AA} ($b \rightarrow J/\psi$) > R_{AA} (prompt D^0) → Flavor hierarchy

Flavor Dependent Energy Loss

arXiv:1810.11102
PLB 782 (2018) 474

Charm
vs
Beauty (→ D^0)

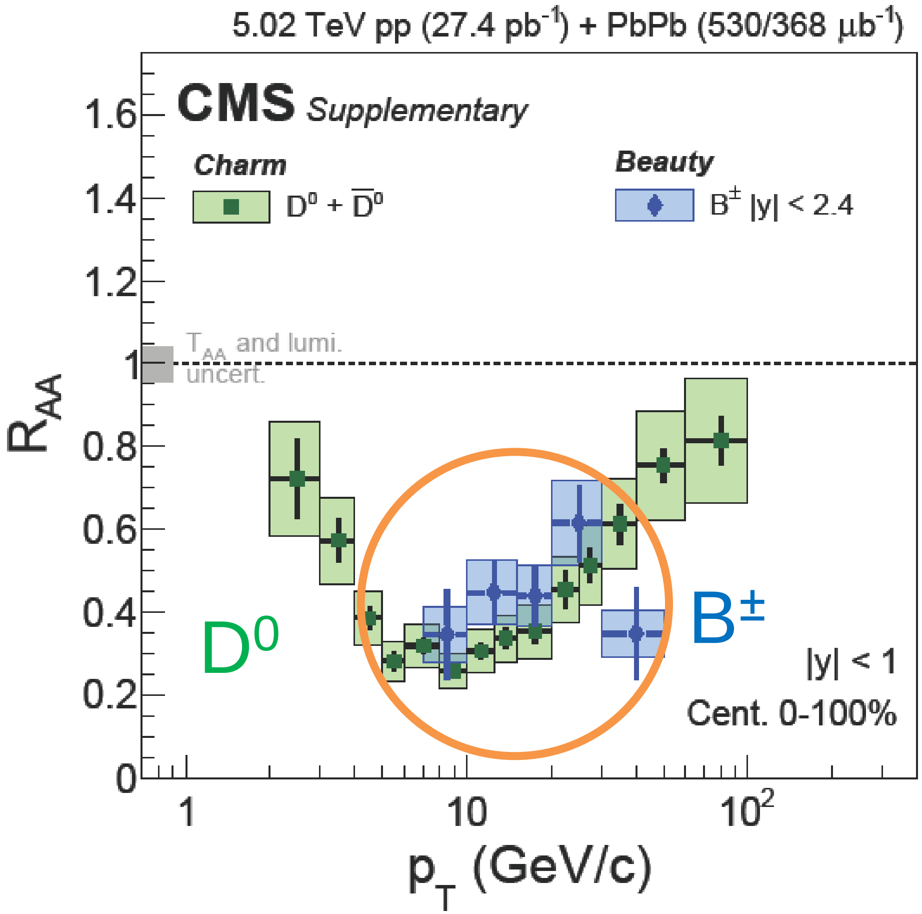


- Low p_T : R_{AA} ($b \rightarrow D^0$) > R_{AA} (prompt D^0) → Flavor hierarchy

Flavor Dependent Energy Loss

PRL 119 (2017) 15230
PLB 782 (2018) 474

Charm
vs
Beauty meson



- Mid p_T : 1st measurement of fully reconstructed $B^{\pm}$
  → Large uncertainties will be reduced with 2018 Data.

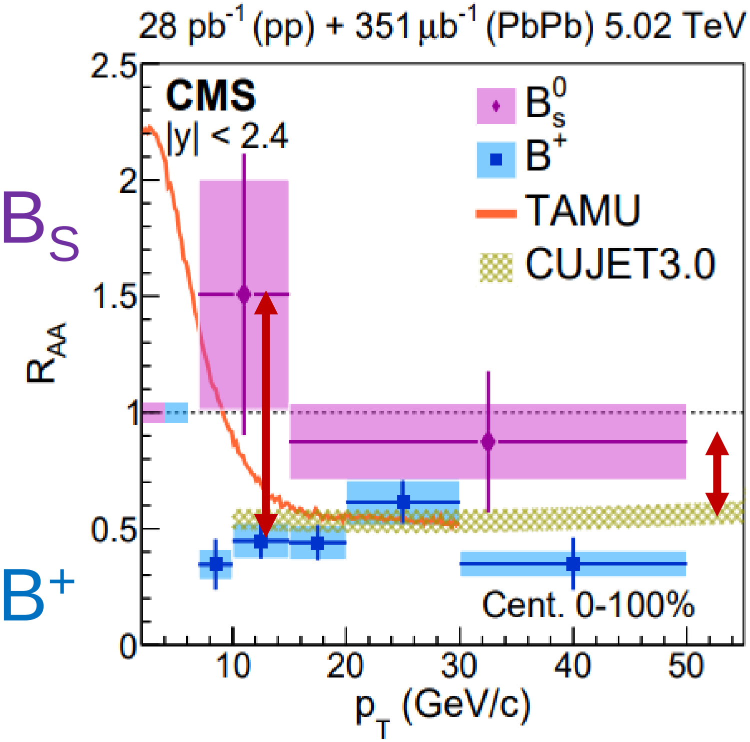
Heavy Flavor Hadronization

PLB 796 (2019) 168

arxiv:1906.03322

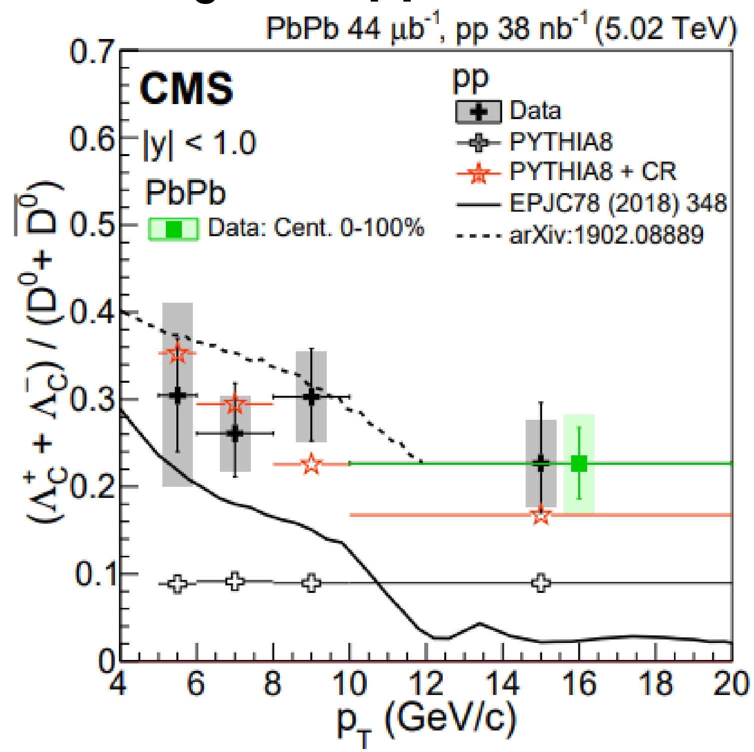
B_S/B^+ in PbPb

B_S



B^+

Λ_C/D^0 in pp and PbPb



- 1st measurement of B_S hadronization in PbPb.
- Indication of enhanced B_S production over B^+ in PbPb.

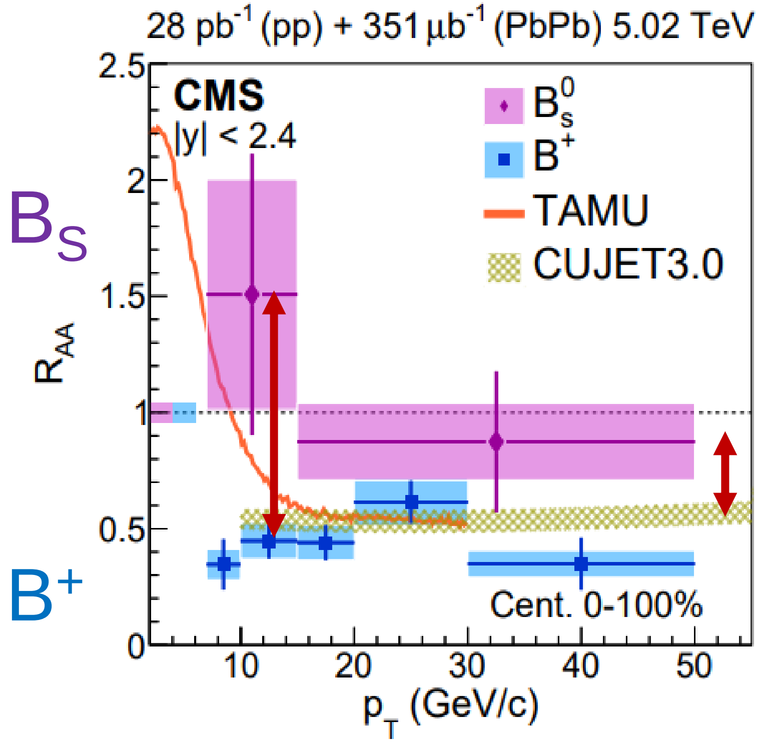
- 1st Measurement of Λ_C in PbPb at high p_T

Heavy Flavor Hadronization

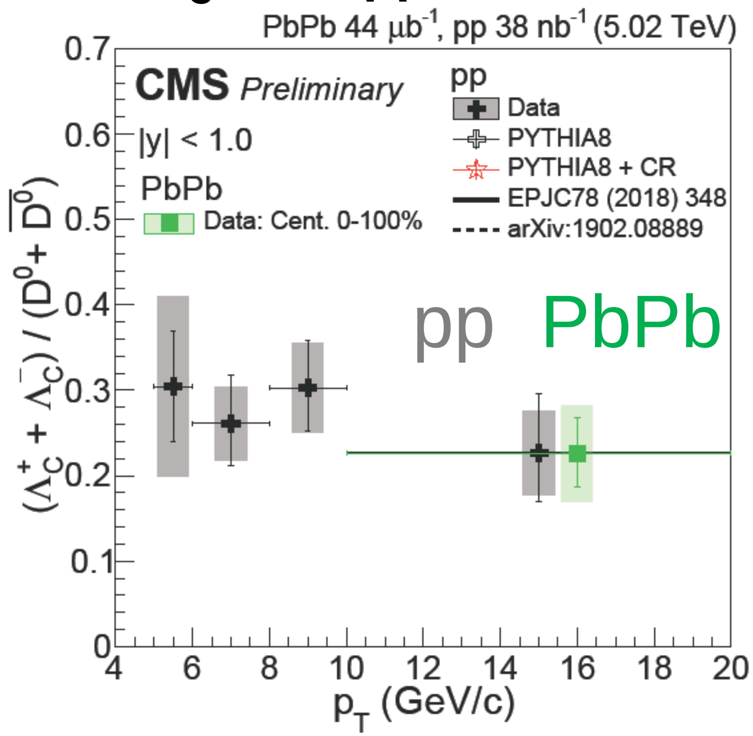
PLB 796 (2019) 168

arxiv:1906.03322

B_S/B^+ in PbPb



Λ_C/D^0 in pp and PbPb



- 1st measurement of B_S hadronization in PbPb.
- Indication of enhanced B_S production over B^+ in PbPb.

- Is Λ_C/D^0 enhanced in PbPb than in pp?
- No significant indication at high p_T

Quarkonia Sequential Suppression in PbPb

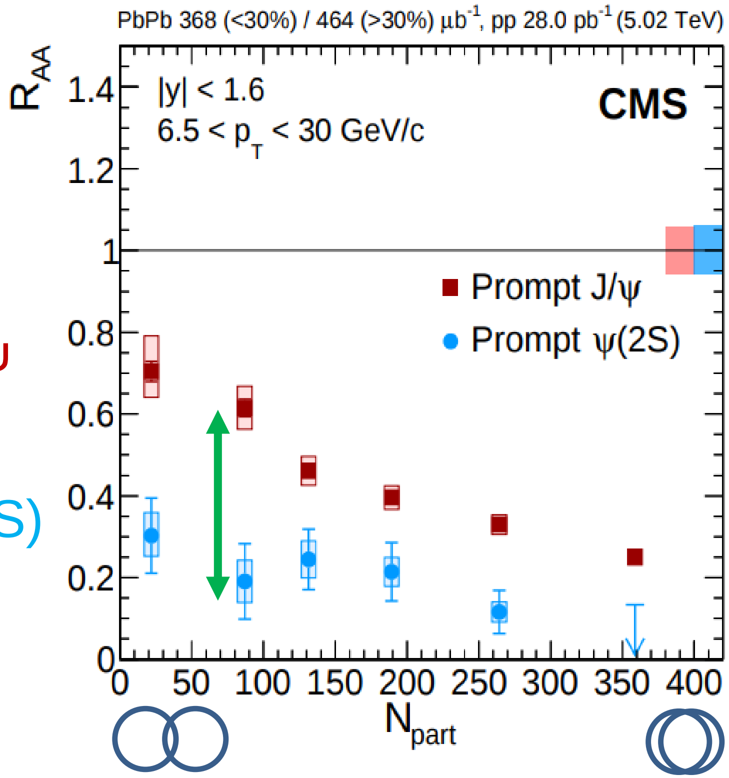
EPJC 78 (2018) 509

PLB 790 (2019) 270

Charmonia

J/ψ

ψ(2S)

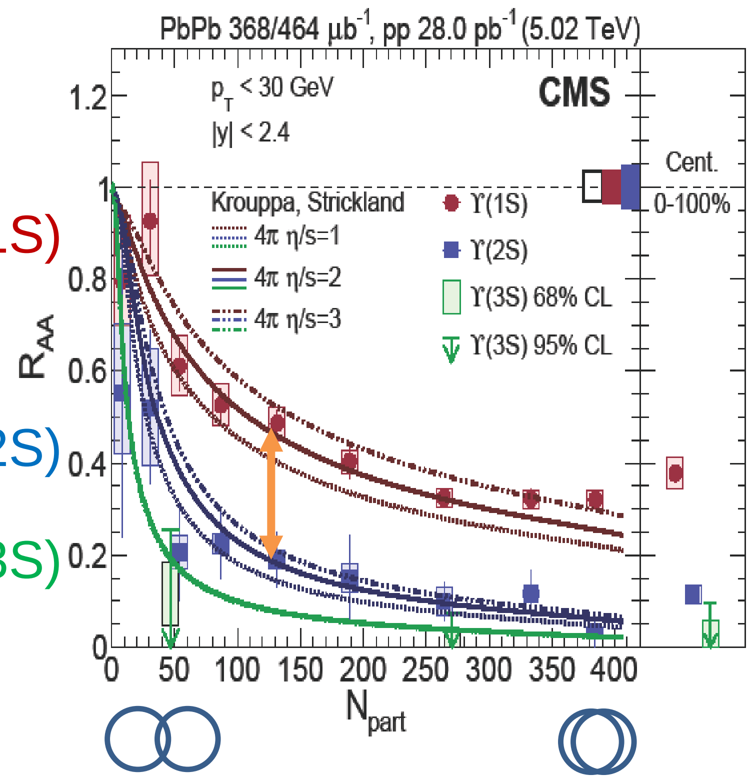


Bottomonia

Υ(1S)

Υ(2S)

Υ(3S)

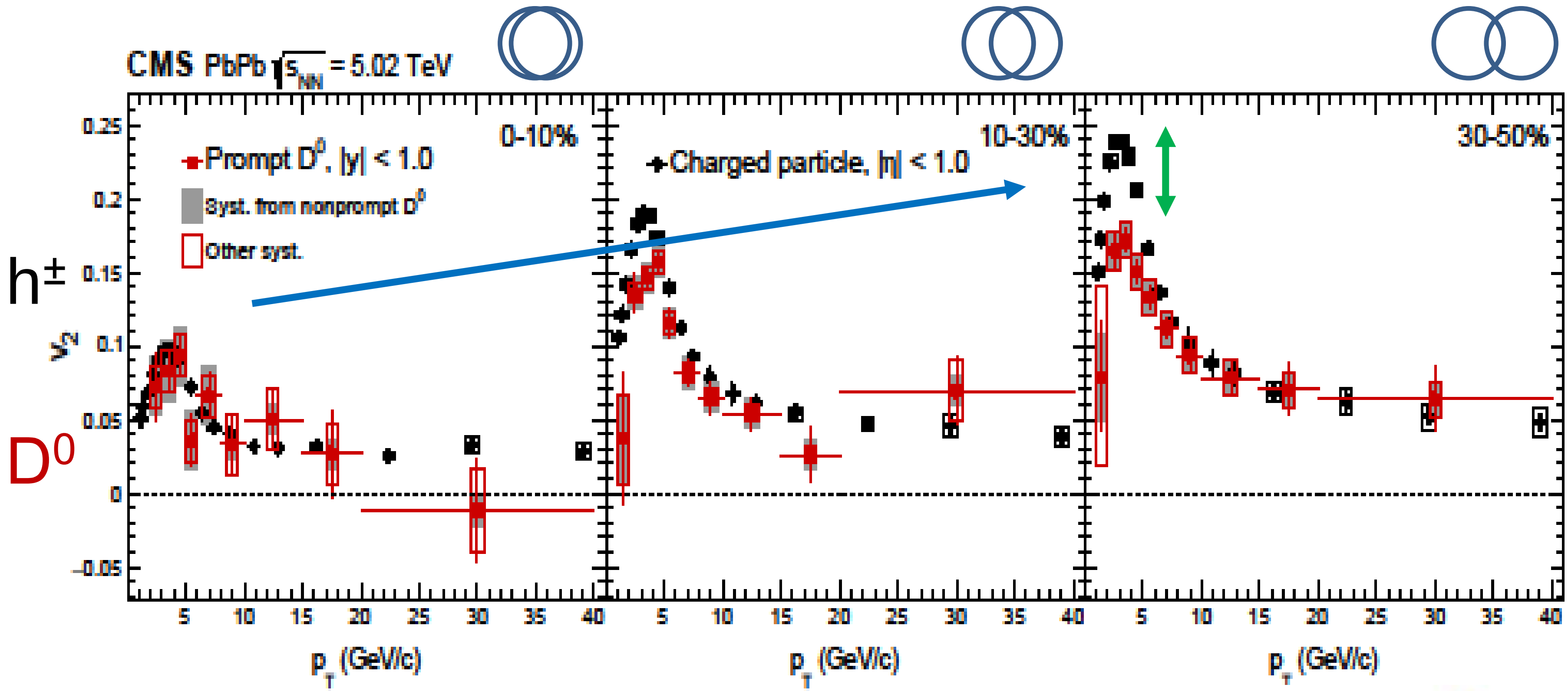


- ψ(2S) shows stronger suppression than J/ψ

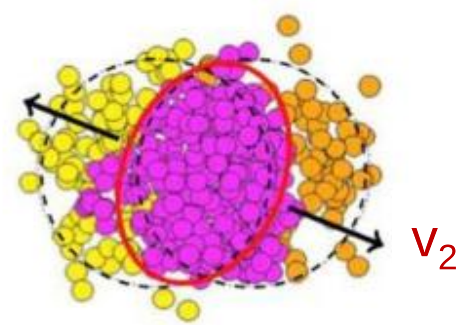
- No sign of Υ(3S) in 2015 PbPb.
- R_{AA} (Υ(1S)) > R_{AA} (Υ(2S))
- Agree with models w/ and w/o Υ regeneration

Heavy Quark Flow: Charm

PRL 120 (2018) 202301



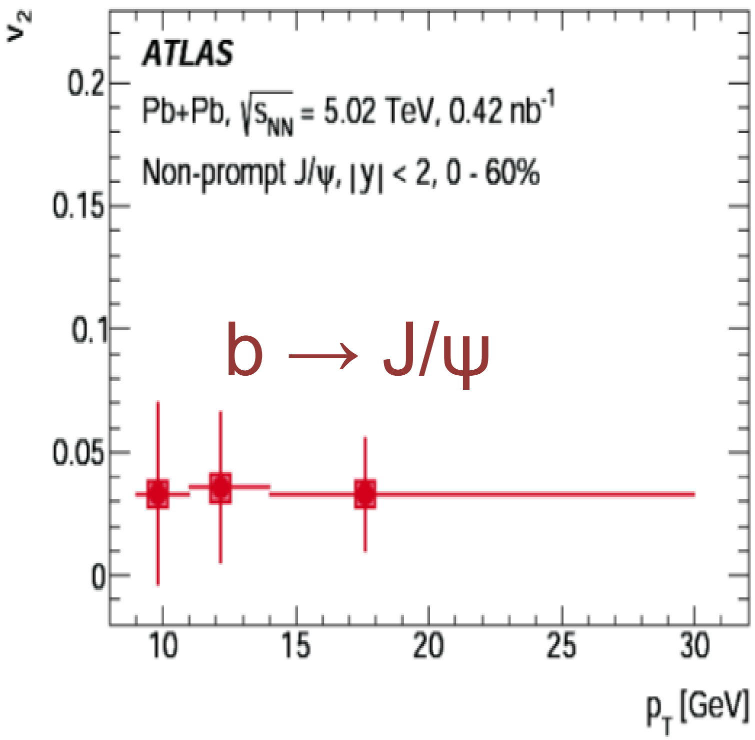
- v_2 peaks at around 3 GeV
- v_2 (D^0) < v_2 (charged particles)
- v_2 increase from central to peripheral events



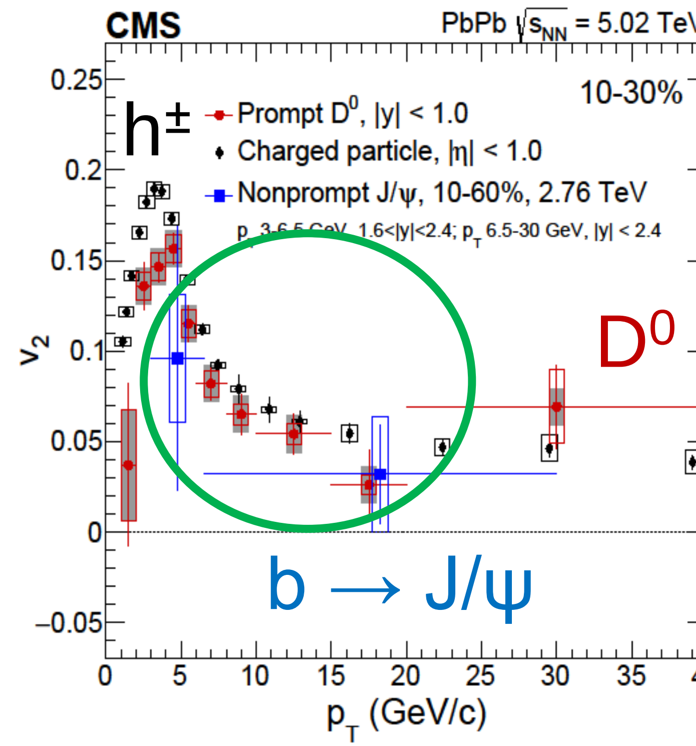
Heavy Quark Flow: Beauty

EPJC 78 (2018) 762

PRL 120 (2018) 202301



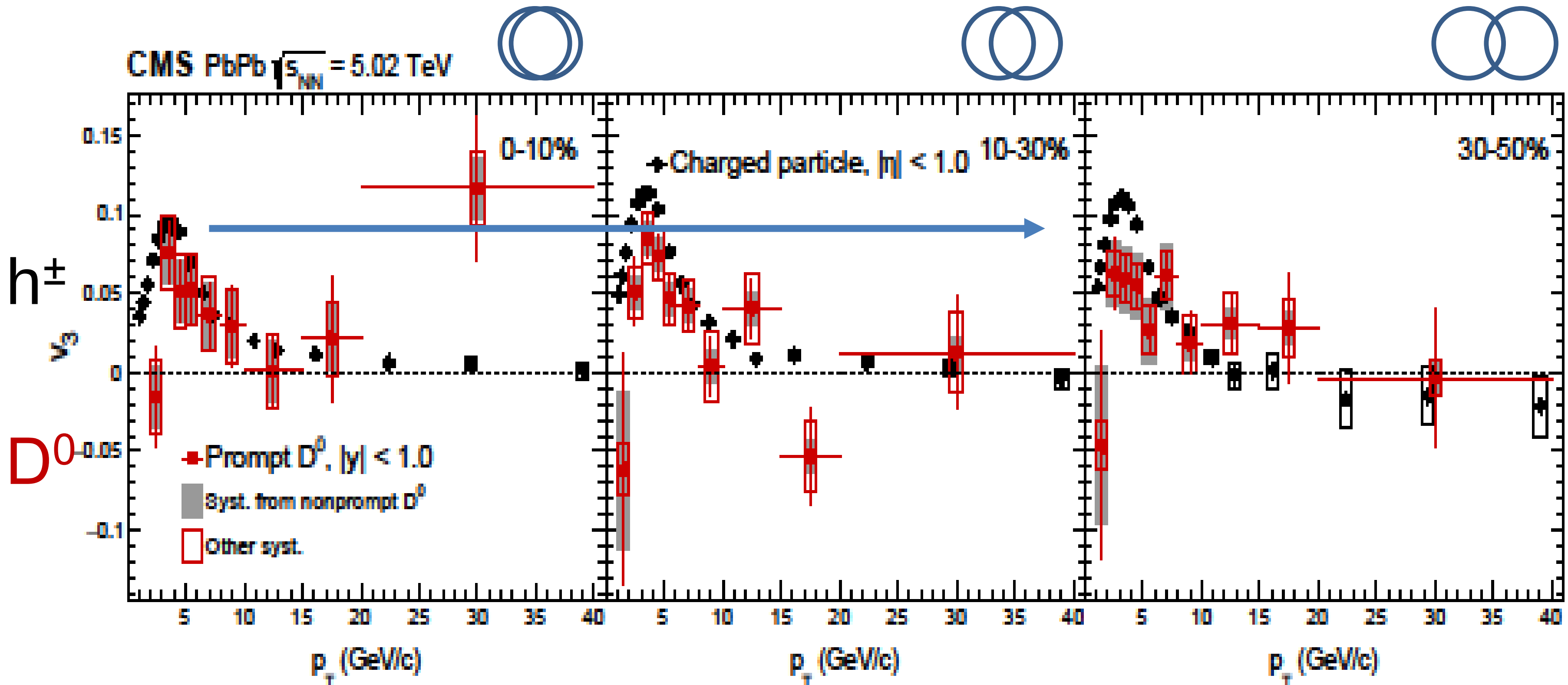
Beauty vs Charm



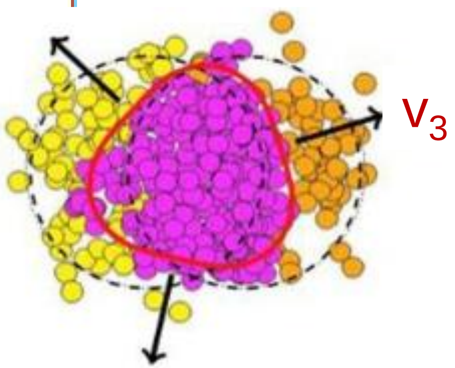
- Indication of positive v_2 from beauty quark
- Is v_2 (beauty) < v_2 (charm) ? → Will be explored further.

Probing Initial Fluctuation by D^0 v_3

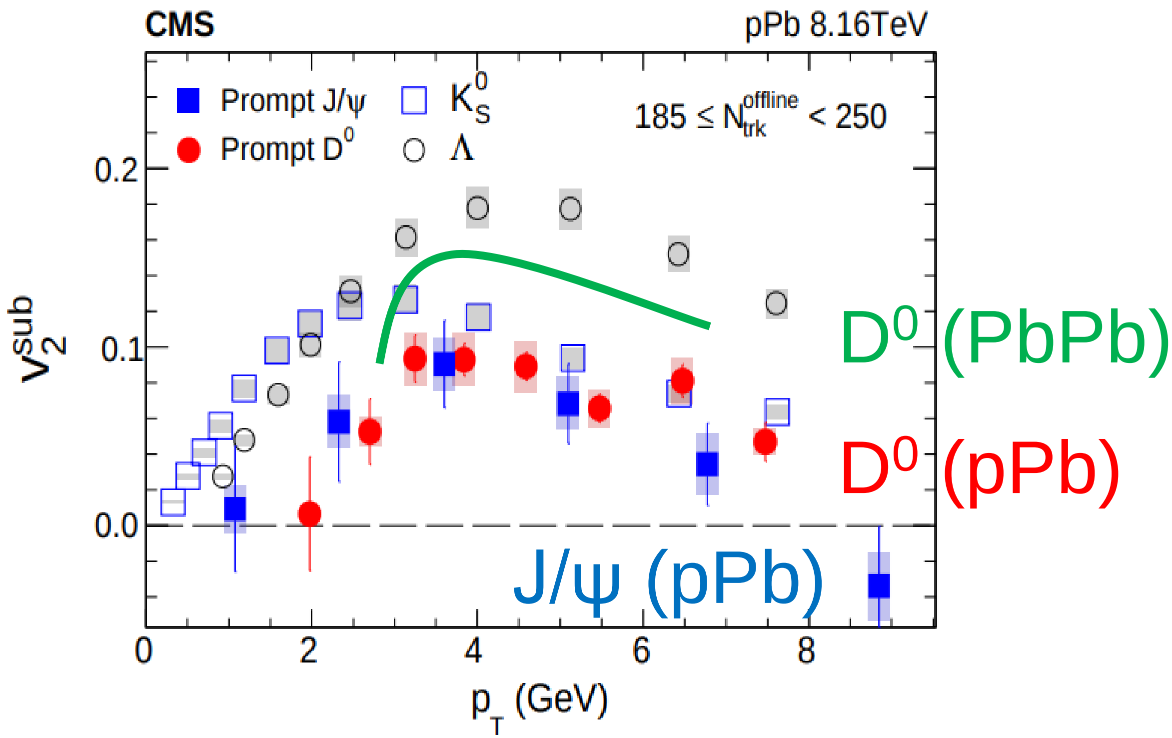
PRL 120 (2018) 202301



- 1st measurement of nonzero D^0 v_3 ≈ charged hadrons
- No significant centrality dependence
- Charm can feel small initial stage fluctuations



PRL 121 (2018) 082301
PLB 791 (2019) 172



- Positive prompt D^0 v_2 in pPb (< D^0 v_2 in PbPb)
- v_2 (prompt J/ψ = $c\bar{c}$) ≈ v_2 (prompt D^0 = $c\bar{u}$) ≠ 0 → Charm indeed flows!

Heavy Quarkonia in Small Systems

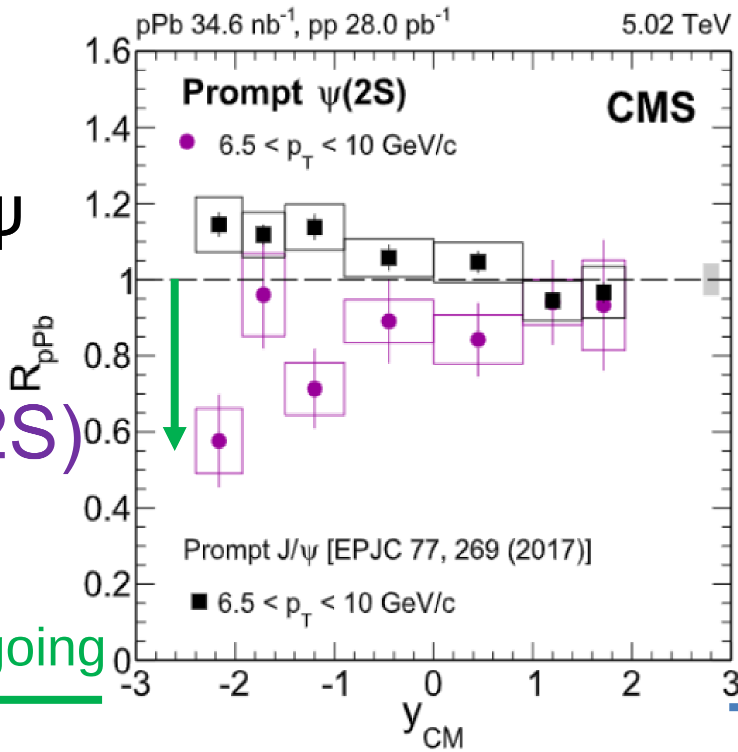
PLB 790 (2019) 509

ψ(2S) and J/ψ in pPb

J/ψ

ψ(2S)

Pb-going

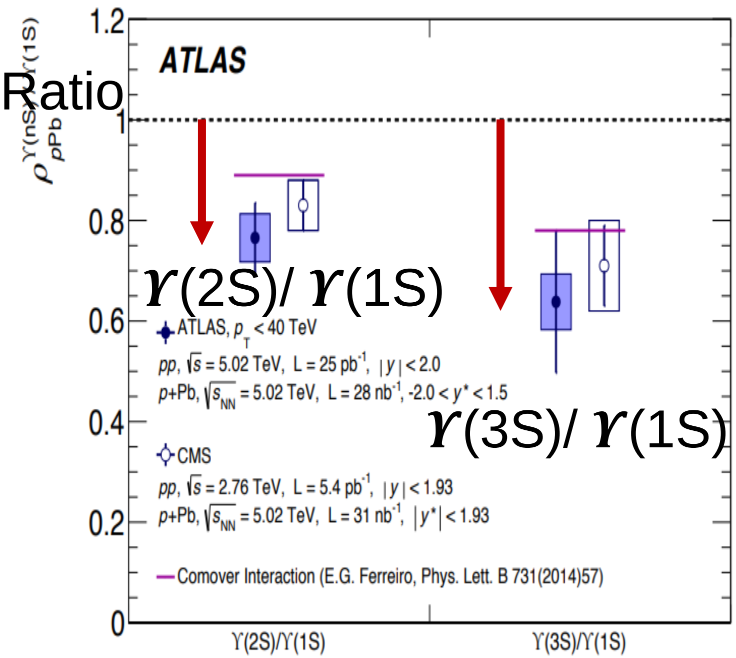


p-going

EPJC 78 (2018) 762

ϒ(nS)/ϒ(1S) in pPb

R_{AA} Ratio



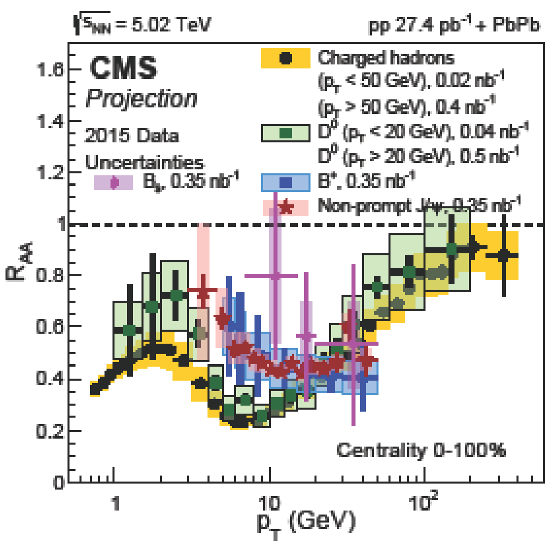
- Suppression of prompt ψ(2S) in Pb-going direction
- Different behavior of ψ(2S) and J/ψ cannot be explained by CNM only.

- ϒ sequential suppression also observed in pPb
  → What is the origin?

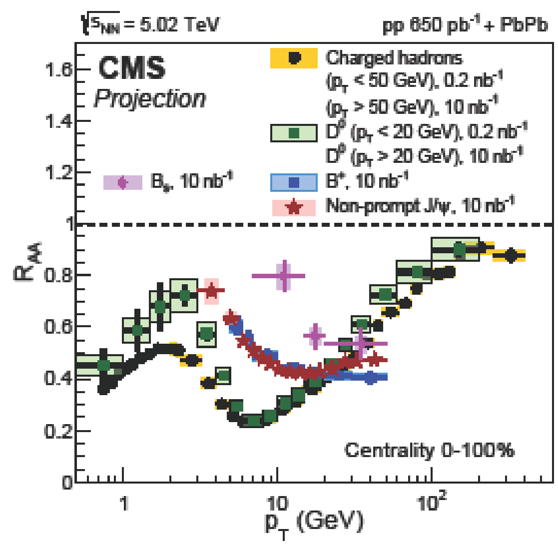
Summary

- Heavy flavor measurement at CMS and ATLAS have explored:
  - Flavor dependent parton energy loss
  - Heavy quark hadronization mechanisms
  - Sequential suppression of heavy quarkonia
  - Initial stage geometry and fluctuation
  - QGP-like properties in small system

- Future upgrades of LHC will increase the statistical significance of heavy flavor measurements and enrich our understanding of QGP.



Current Luminosity



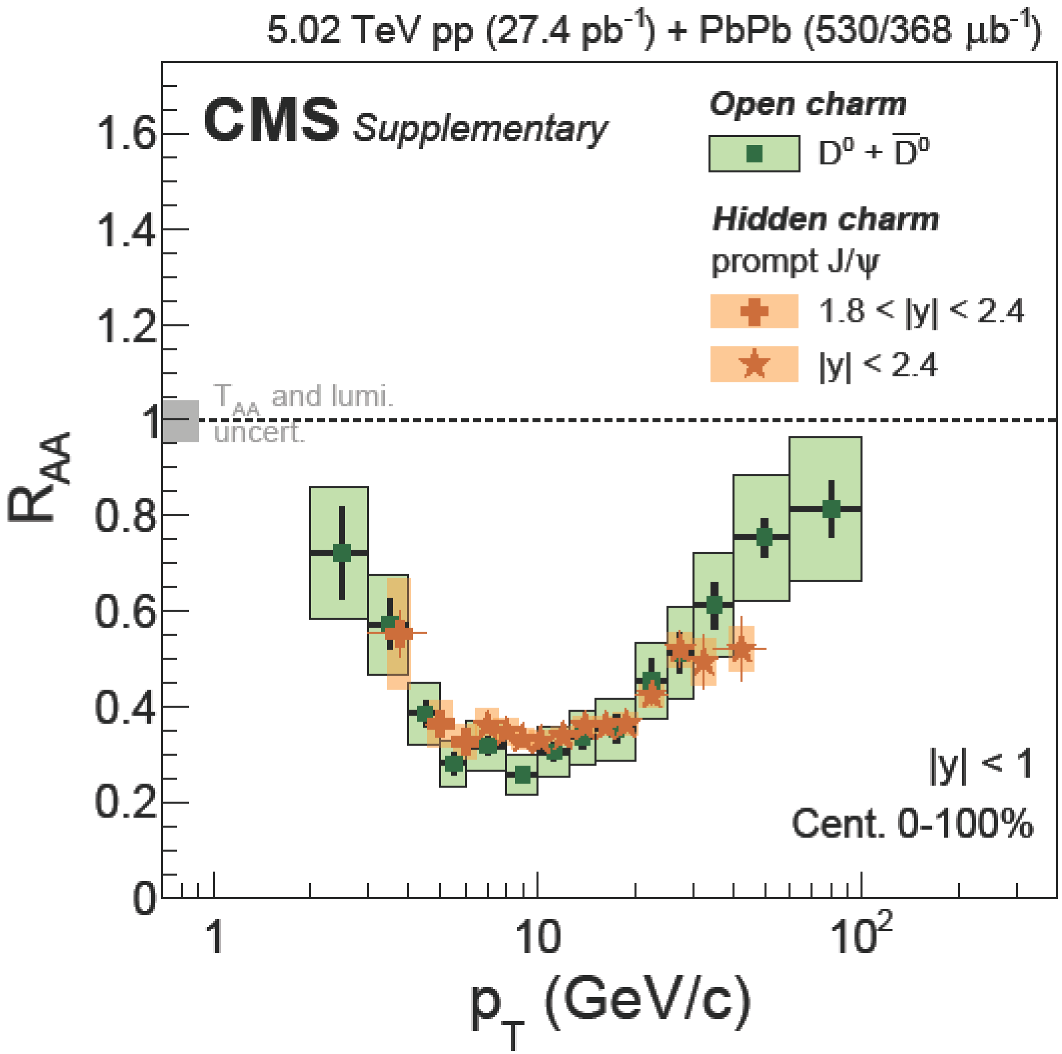
Future Luminosity

arxiv:1812.06772

Backup Slides

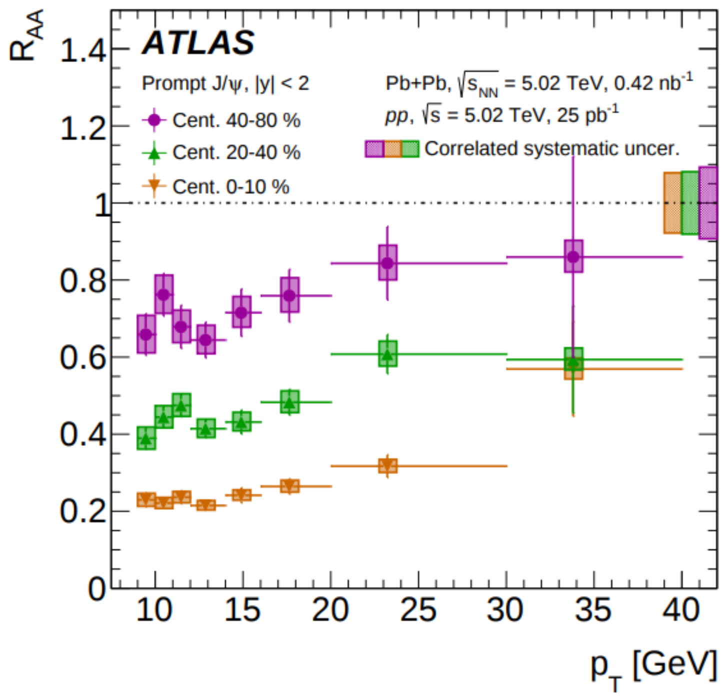
Prompt J/ψ vs D^0

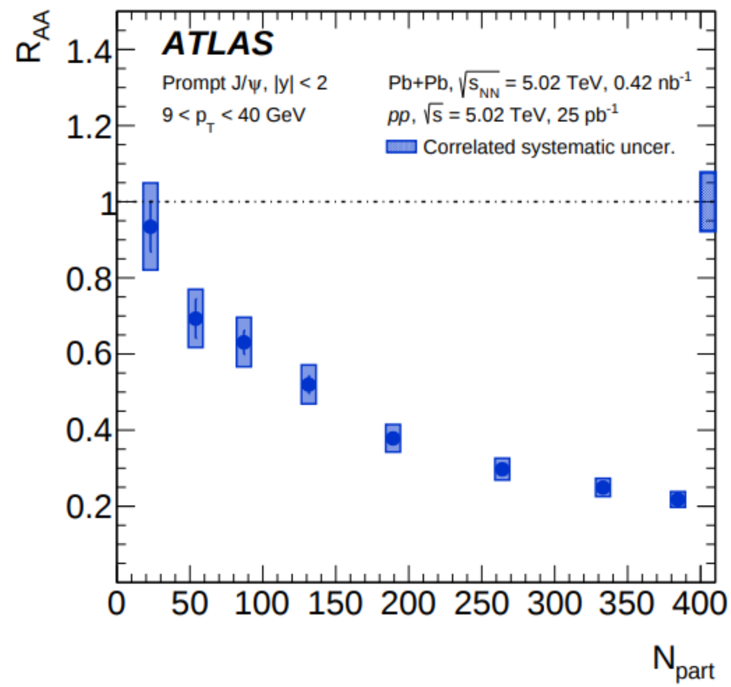
EPJC 78 (2018) 509
PLB 782 (2018) 474



Prompt J/ψ with respect to Centrality

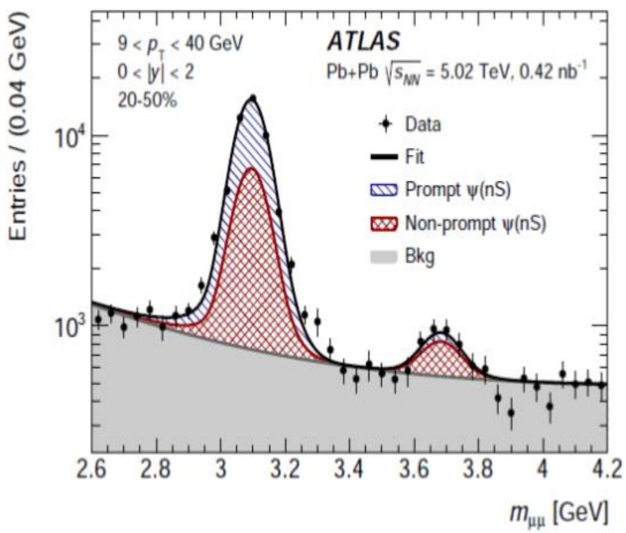
EPJC 78 (2018) 762

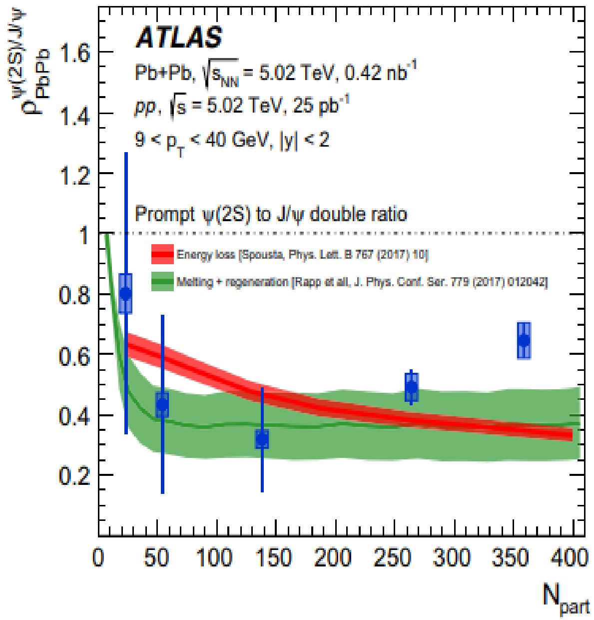


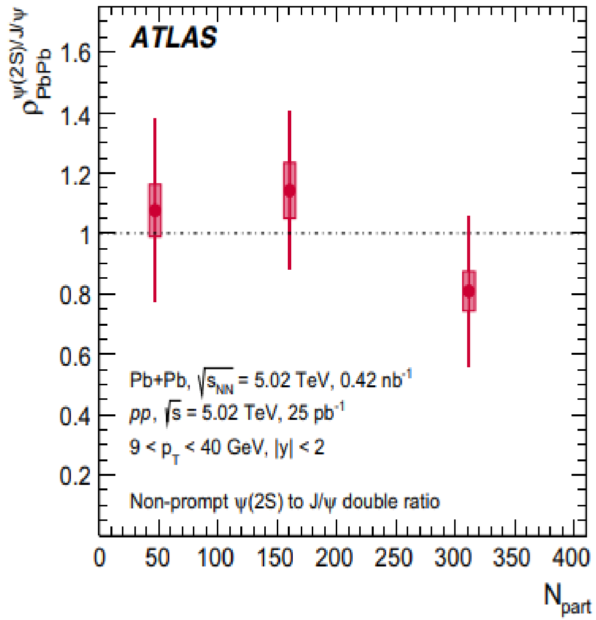


Charmonia in PbPb

EPJC 78 (2018) 762



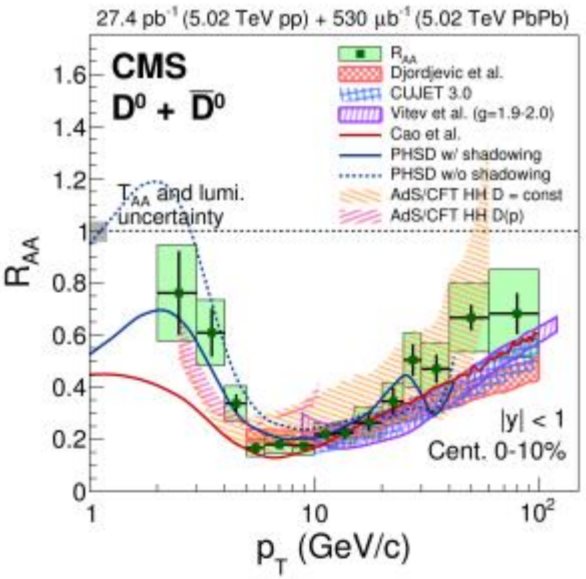


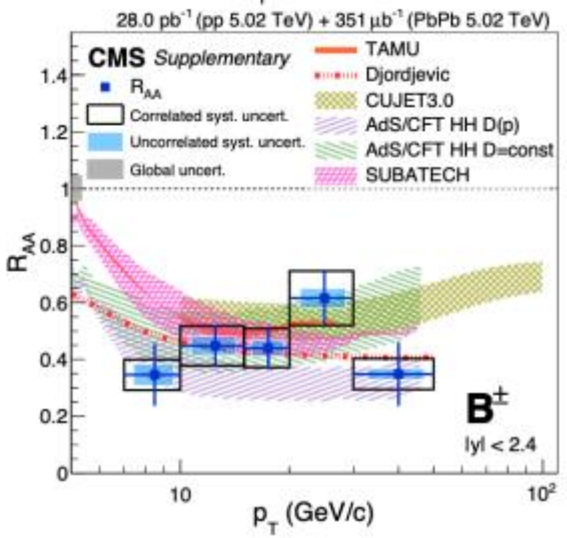


- Suppression of ψ(2S) yield compared to J/ψ.

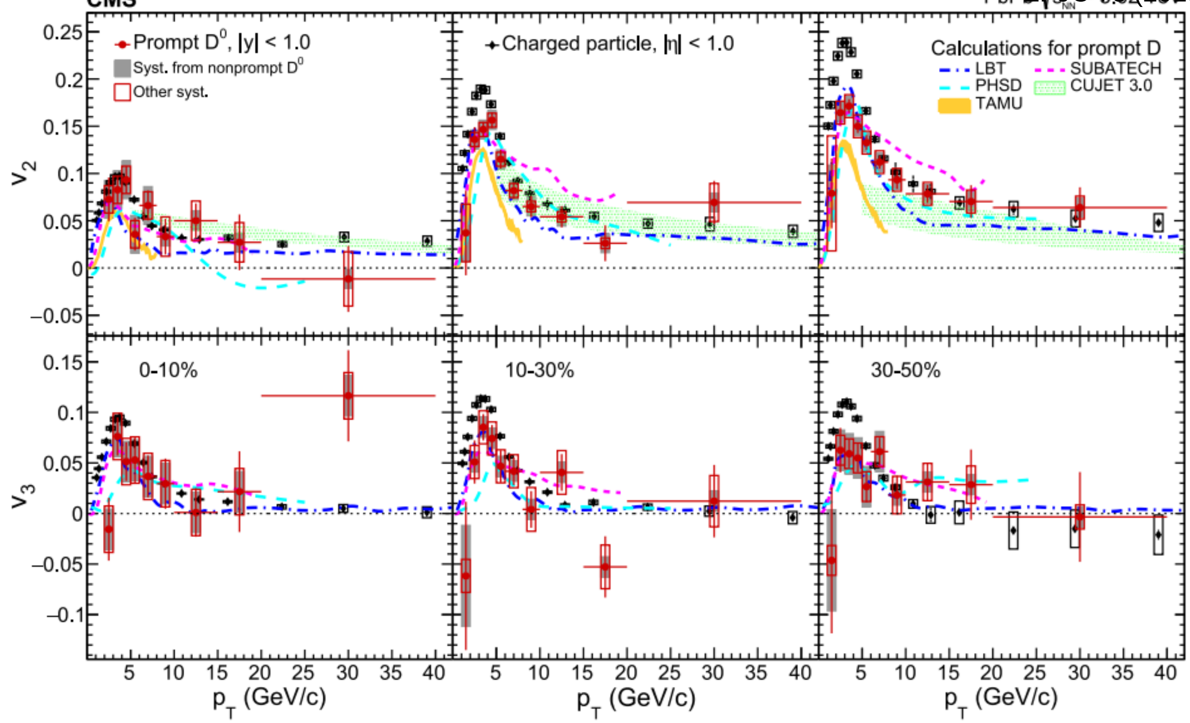
- Double ratio of R_{AA}(ψ(2S)) and R_{AA}(J/ψ).
- Prompt ψ(2S) suppressed more than J/ψ
  → Sequential suppression
  Non-prompt ψ(2S) suppressed by similar amount to J/ψ
  → both are produced in B hadron decays

Theoretical model comparison

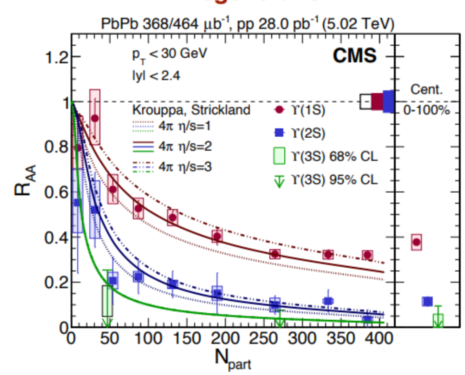




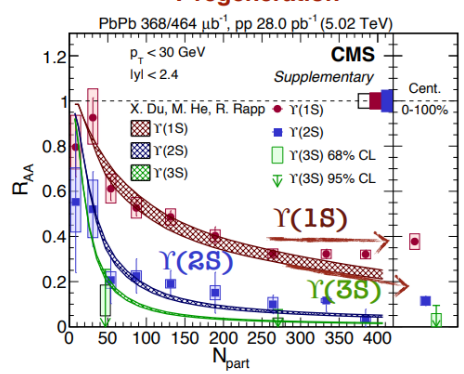
EPJC 78 (2018) 762



R$_{AA}$ vs. model w/o Υ regeneration

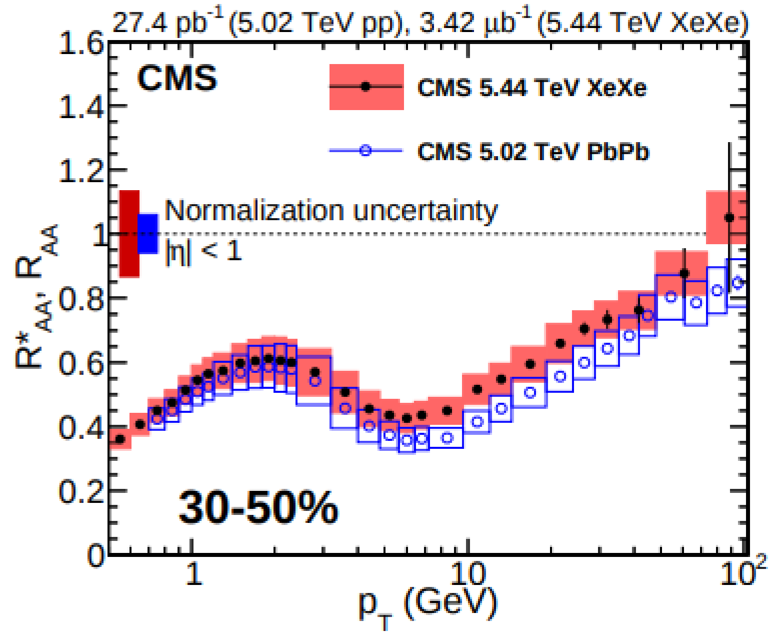


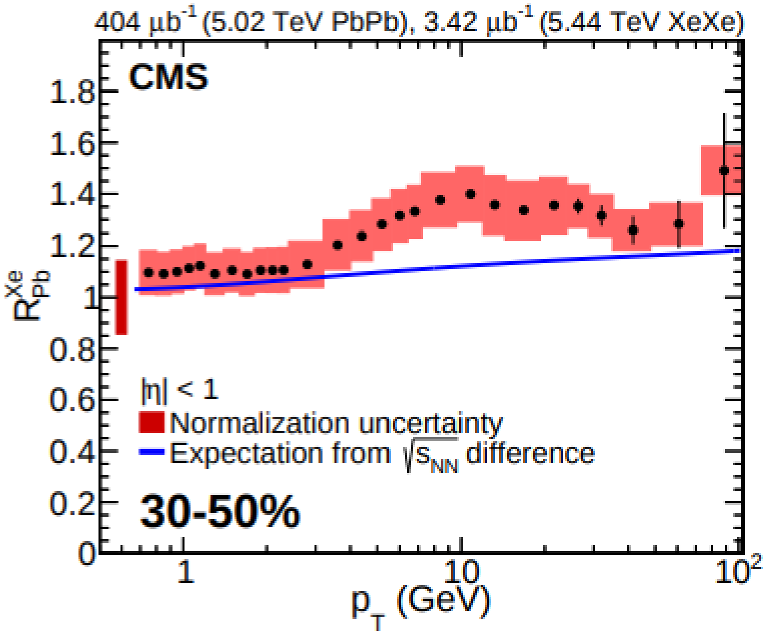
R$_{AA}$ vs. model w/ Υ regeneration



PLB 782 (2018) 474 / PRL 119 (2017) 15230 / PRL 120 (2018) 202301

JHEP 10 (2018) 138





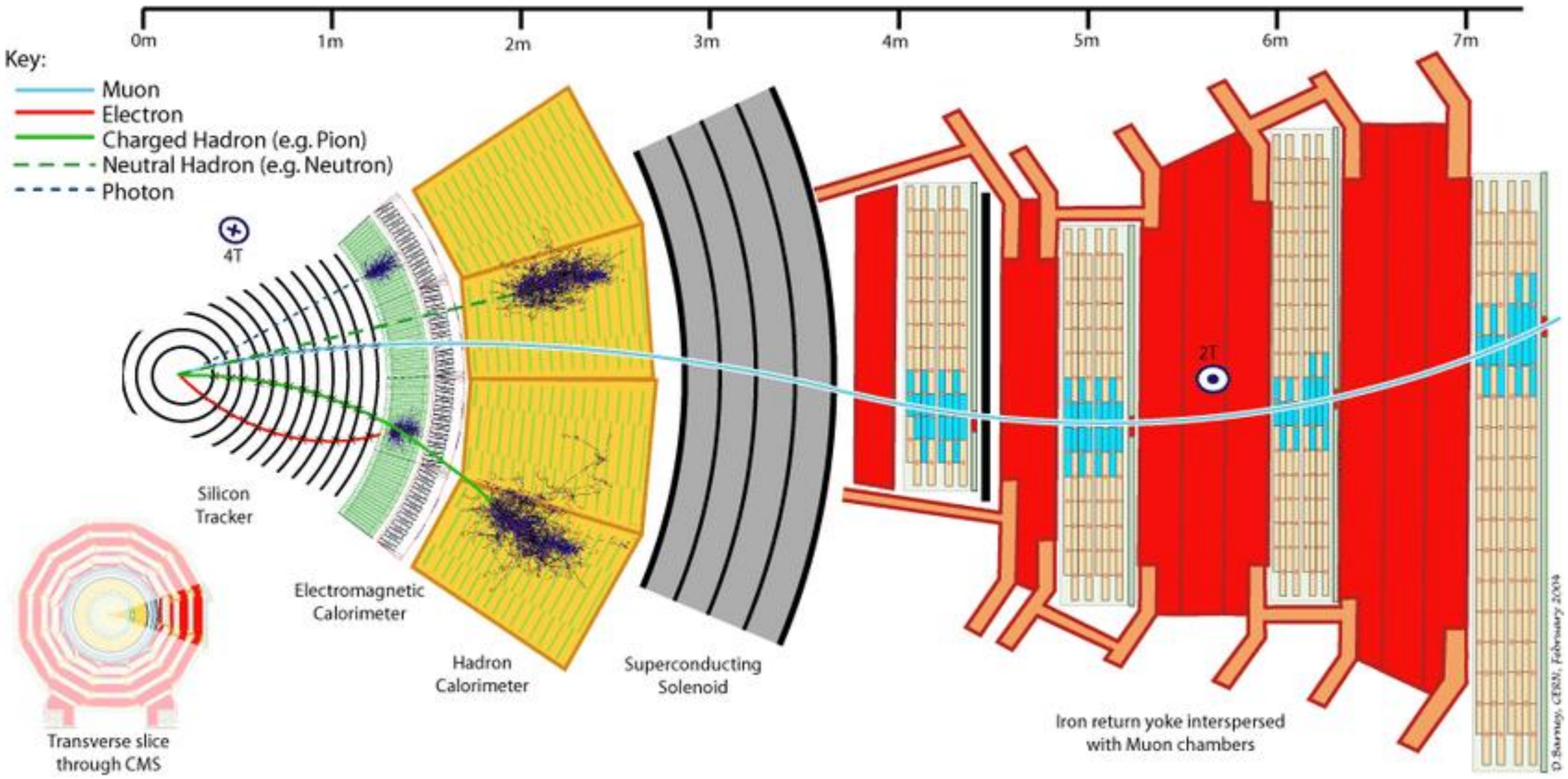
- QGP from different size nuclei Xe and Pb are studied in terms of R_{AA}
  → New way to probe QGP which differs from PbPb, pPb, and pp collision.
- Small system Xe shows feature slightly less suppression.

Future Plan: High-Luminosity LHC

arxiv:1812.06772

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

- Future improvements will include:
  - Statistics ↑ in low p_T
  - Acceptance ↑ to $|y|< 4$
  - L1 and DAQ improvements (up to 60 GB/s) → Sophisticated trigger.
  - Time resolution up to 30ps → Allow PID with time-of-flight


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D Barney, CERN, February 2004

ATLAS Detector @LHC