Part of

Heavy Flavor at the LHC

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RBRC Workshop: Predictions for sPHENIX
20 July 2022

MITHIG group's work was supported by US DOE-NP

The Road: Past, Present and Future

Run 1	Run 2	Long Shutdown 2	Run 3	LS 3	Run 4	LS 4
	PbPb (2.2 nb^{-1}) pPb (0.18 pb^{-1})		PbPb (6 nb^{-1}) pPb (0.5 pb^{-1}) pO/OO	CMS/ATLAS Phase-2 upgrades	PbPb (7 nb^{-1}) pPb (0.5 pb^{-1})	

2015 - 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032

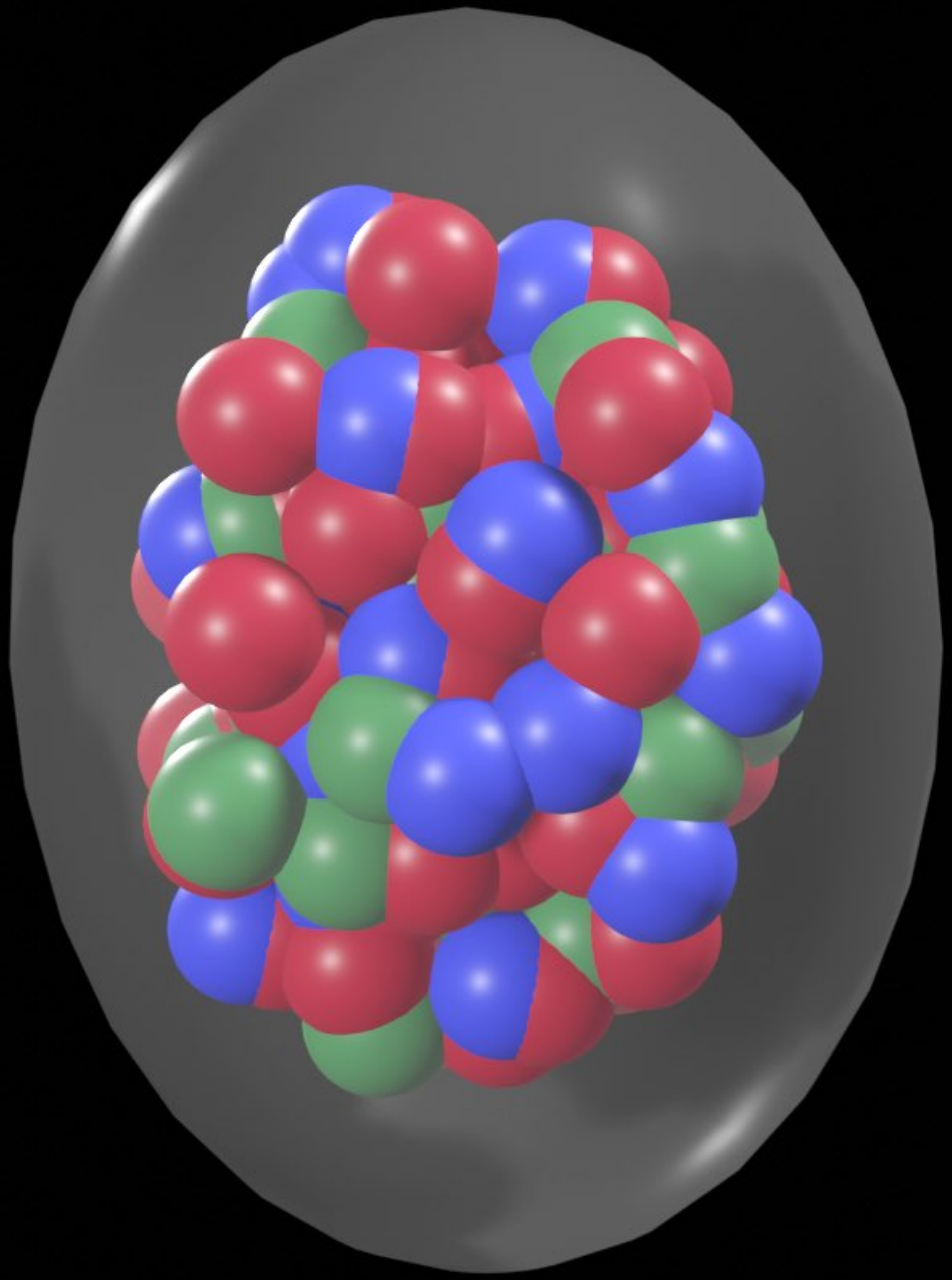
We are here !

sPHENIX 23-35

AuAu
(32 nb^{-1})
pAu
(0.11 pb^{-1})

- High precision at Low p_T
- Jets with full HCAL
- Different collision systems from LHC

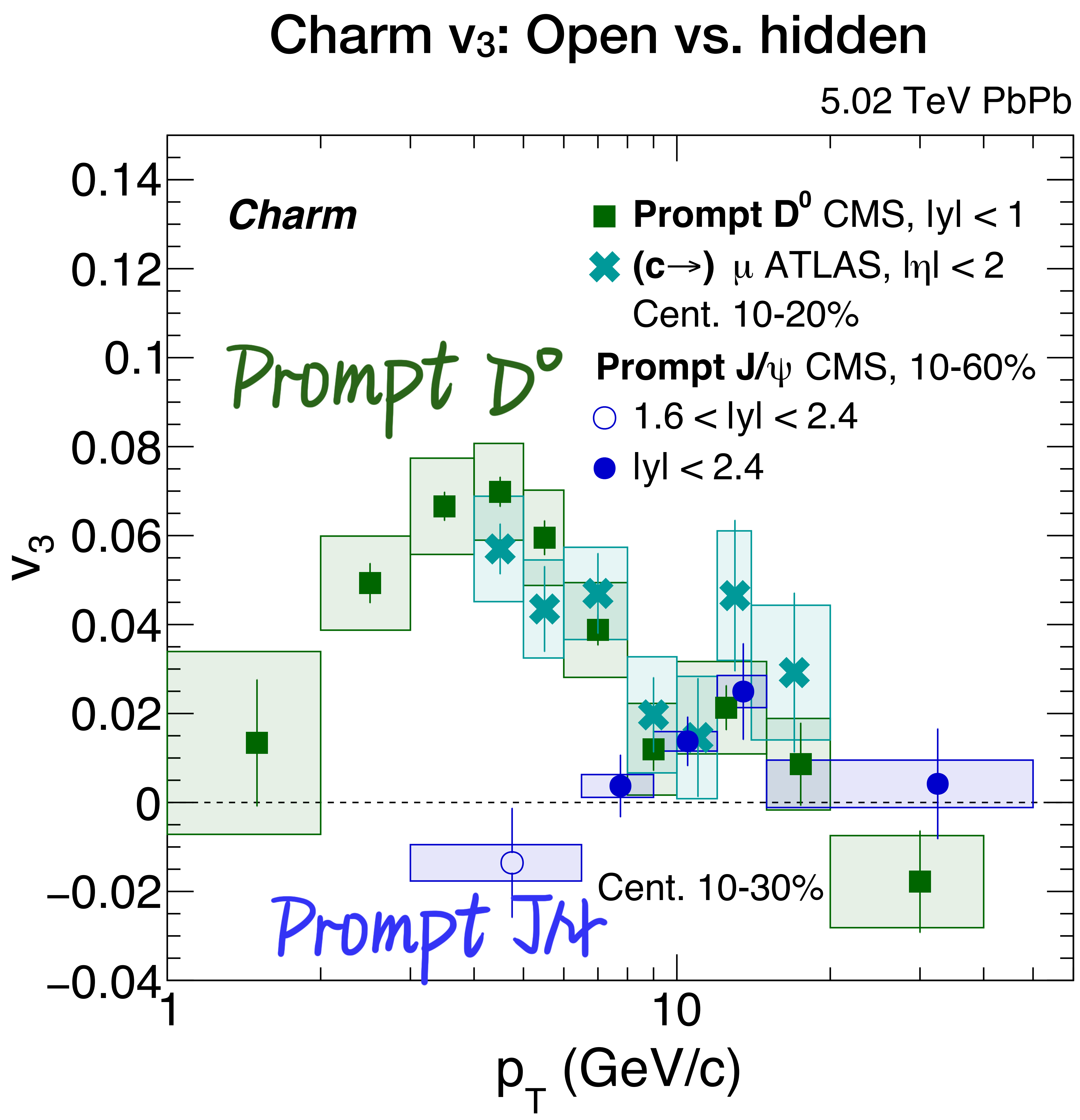
Section I



Initial stage

Click to see animation ➥

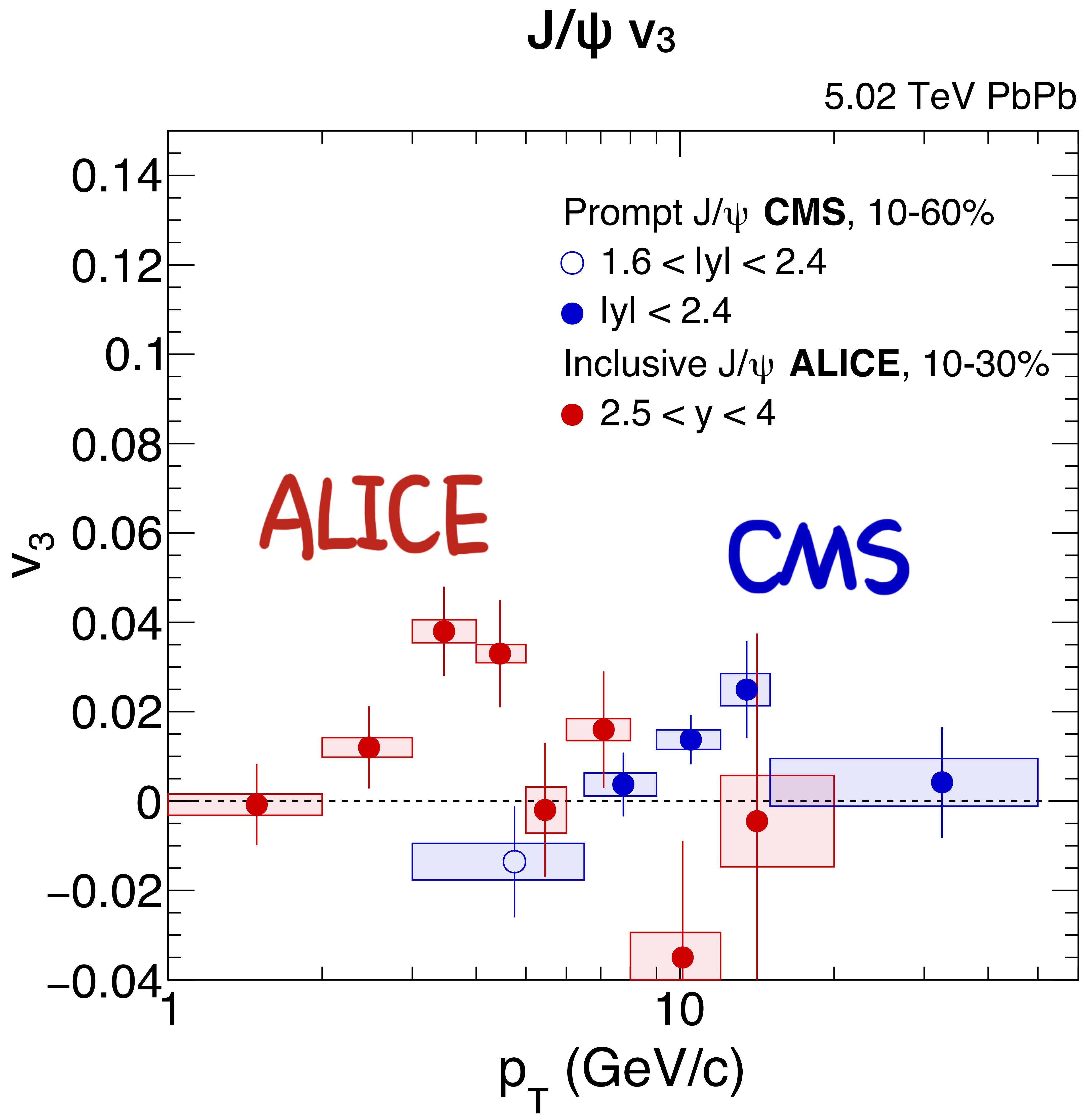
Probe Initial Fluctuations: Charm v_3



- Significant non-zero open charm v_3
  - so charm can see initial fluctuations?
- v_3 (Prompt D^0) > 0 vs. v_3 (Prompt J/ψ) ≈ 0
  - *Is v_3 of D^0 picked from light quarks?*

PLB 816 (2021) 136253
PLB 807 (2020) 135595
CMS-PAS-HIN-21-008

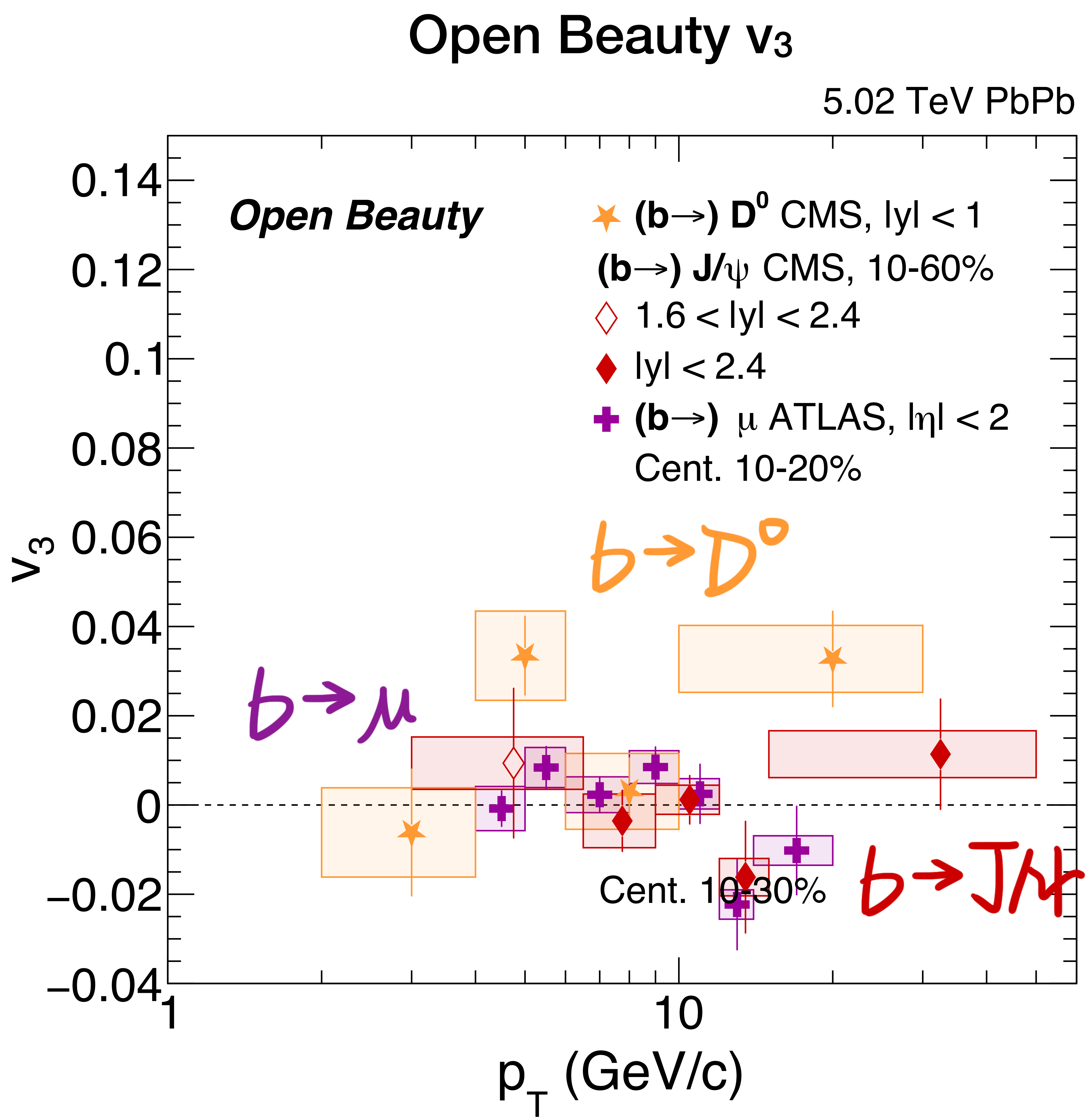
Probe Initial Fluctuations: Charm v_3



- Can charm see initial fluctuations?
- *Is there J/ψ v_3 signal?*
  - Difference between CMS and ALICE
  - Rapidity difference?
  - Need to follow up in Run 3
- sPHENIX access to low p_T is crucial!

JHEP 10 (2020) 141
CMS-PAS-HIN-21-008

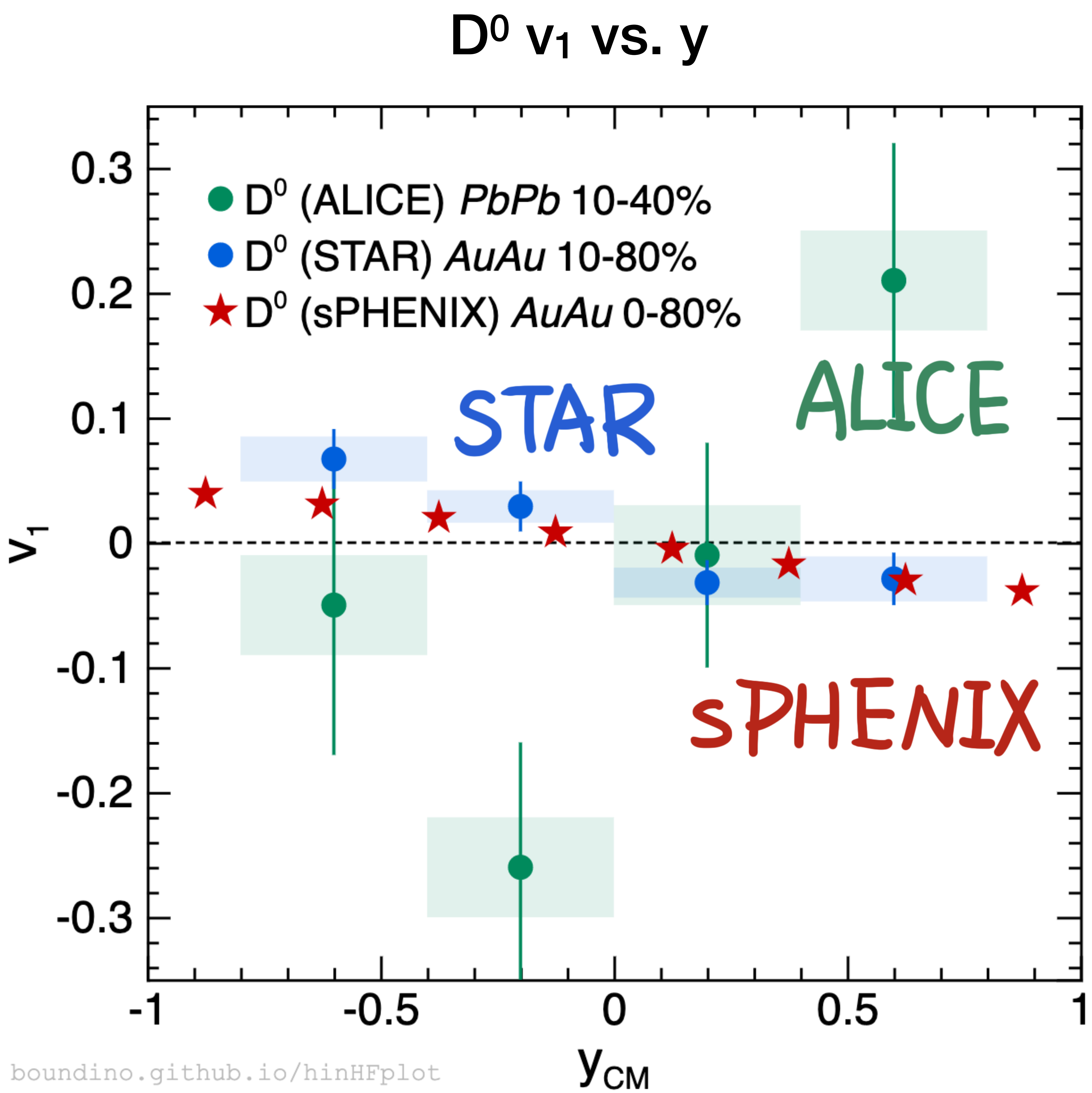
Probe Initial Fluctuations: Beauty v_3



- Beauty v_3 statistically consistent with zero
  ➜ Flavor dependent sensitivity to initial state
  ➜ Recombination component of B is small?
- *Heavy flavor v_3 at RHIC?*

CMS-PAS-HIN-21-003
CMS-PAS-HIN-21-008
PLB 807 (2020) 135595

D^0 Directed Flow v_1



- Sensitive to initial EM field and tilt
- *Opposite slope of ALICE and STAR?*
  - High precision of sPHENIX may draw the conclusion

PRL 125 (2020) 022301
PRL 123 (2019) 162301

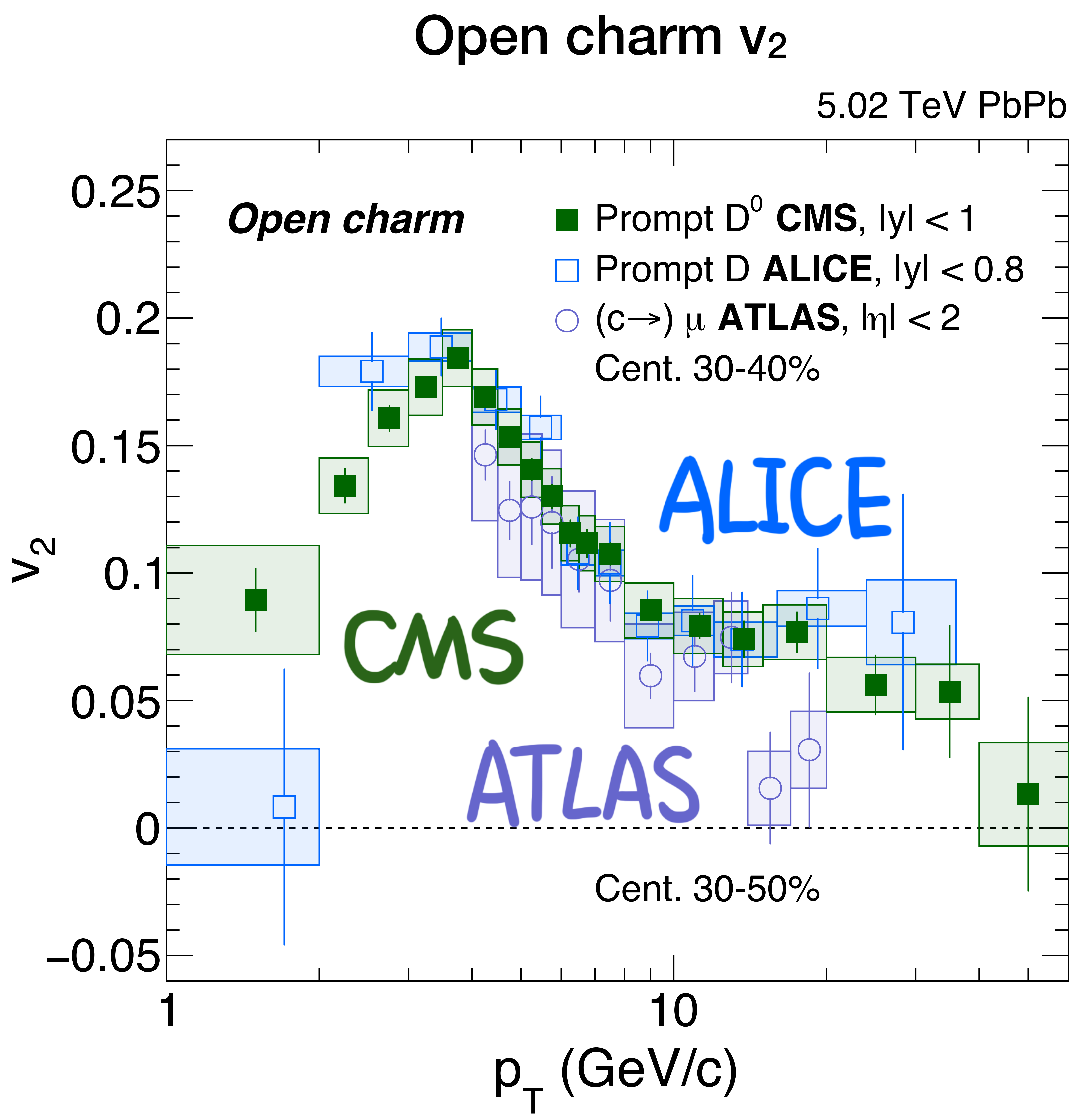
Section II

Click to see animation ↪

Section II.(I)

Heavy Flavor Flow in A-A Collisions

Open Charm v_2 at LHC

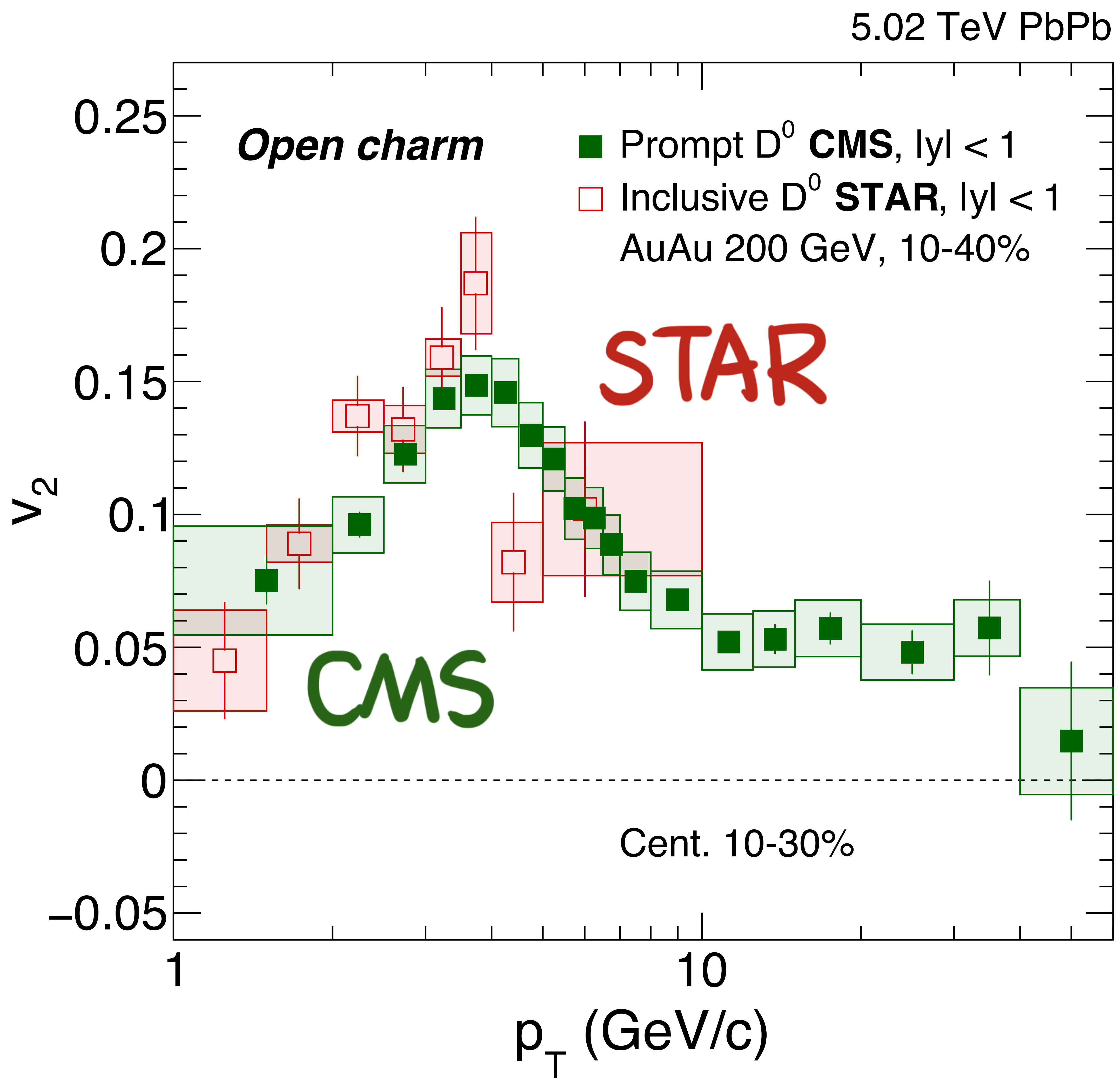


- Open charm v_2 has been well-established
  - Consistent among LHC experiments
  - Prominent flow shape at low p_T
- Non-zero v_2 up to high p_T = 40 GeV
  - Path-length dependence of energy loss

PLB 816 (2021) 136253
PLB 807 (2020) 135595
PLB 813 (2021) 136054

Open Charm v_2: LHC vs. RHIC

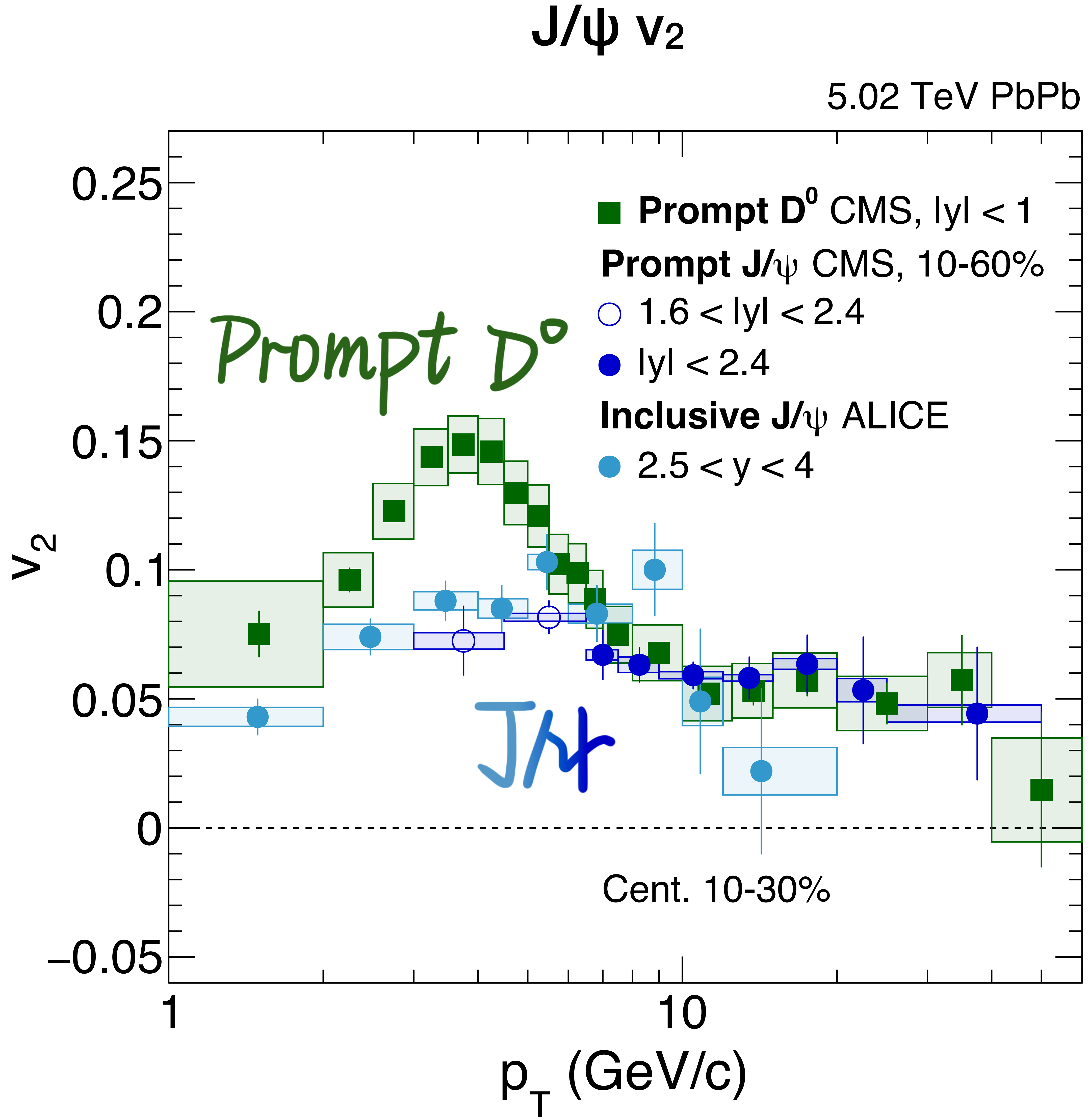
D^0 v_2



- Similar D^0 v_2 in LHC and RHIC
  - *Is this expected considering different collision systems and energies?*
- High precision from sPHENIX

PLB 816 (2021) 136253
PRL 118 (2017) 212301

Charmonium v_2 at LHC



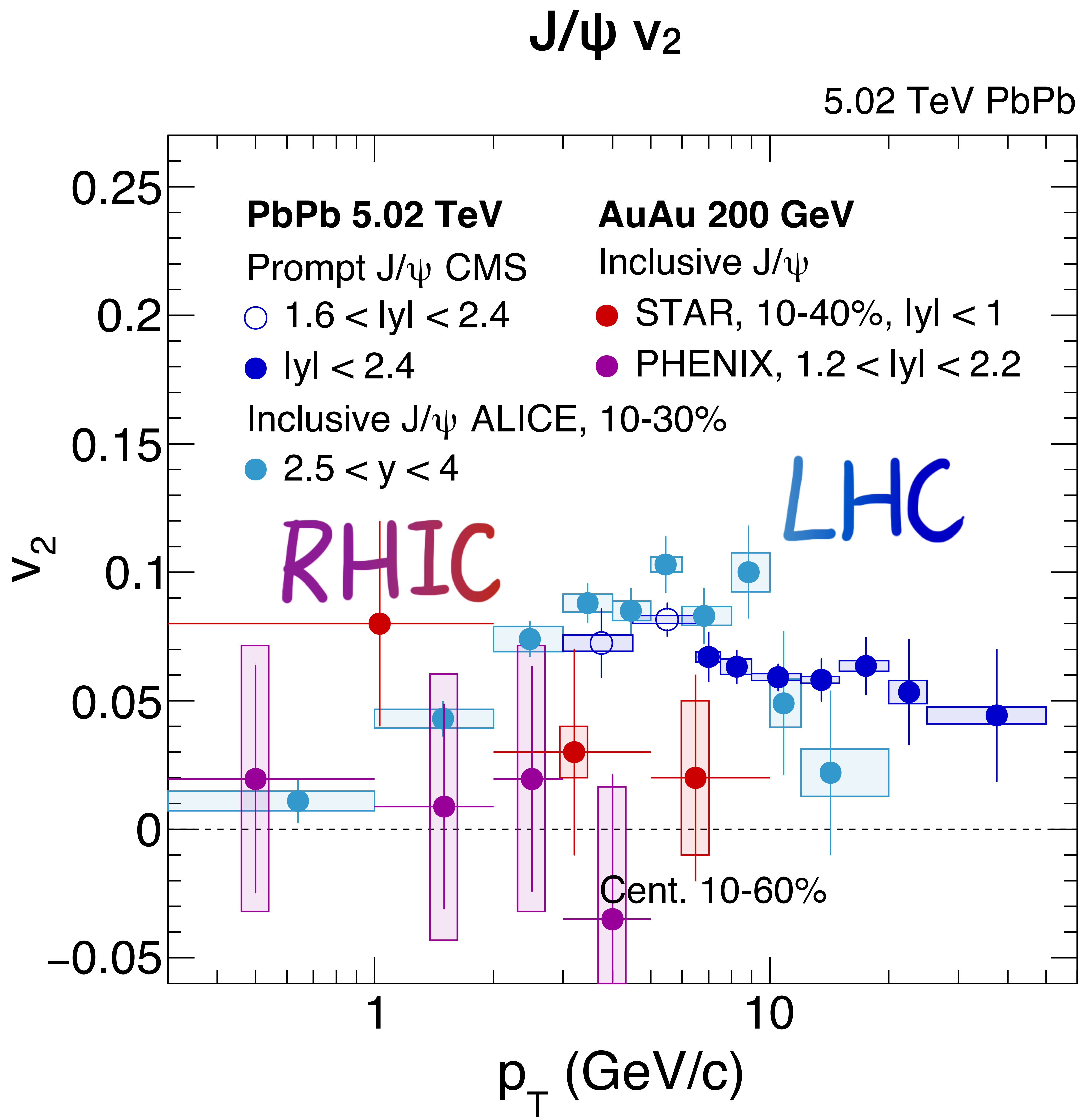
- Significant non-zero J/ψ v_2 at the LHC
- Smaller J/ψ v_2 than D^0 v_2 at low p_T
  - Different constituent quarks
  - Recombination

PLB 816 (2021) 136253

JHEP 10 (2020) 141

CMS-PAS-HIN-21-008

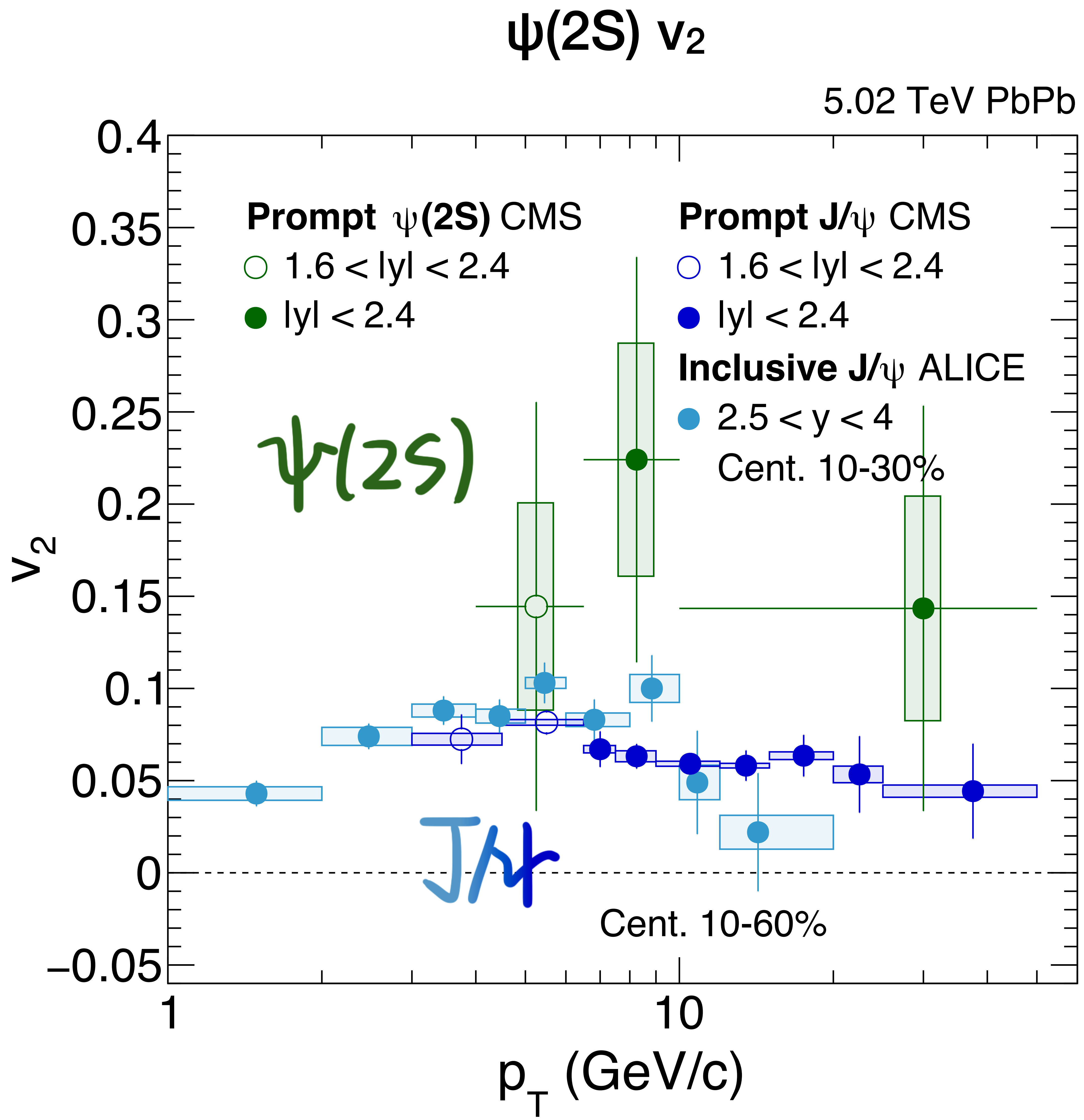
Charmonium v_2: LHC vs. RHIC



- *But no significant J/ψ v_2 at RHIC?*
  - Smaller system, lower energy?
  - Weaker recombination?
  - Current precision is poor
- Interesting for sPHENIX to follow it up

PRL 111 (2013) 052301
PHENIX Preliminary
JHEP 10 (2020) 141
CMS-PAS-HIN-21-008

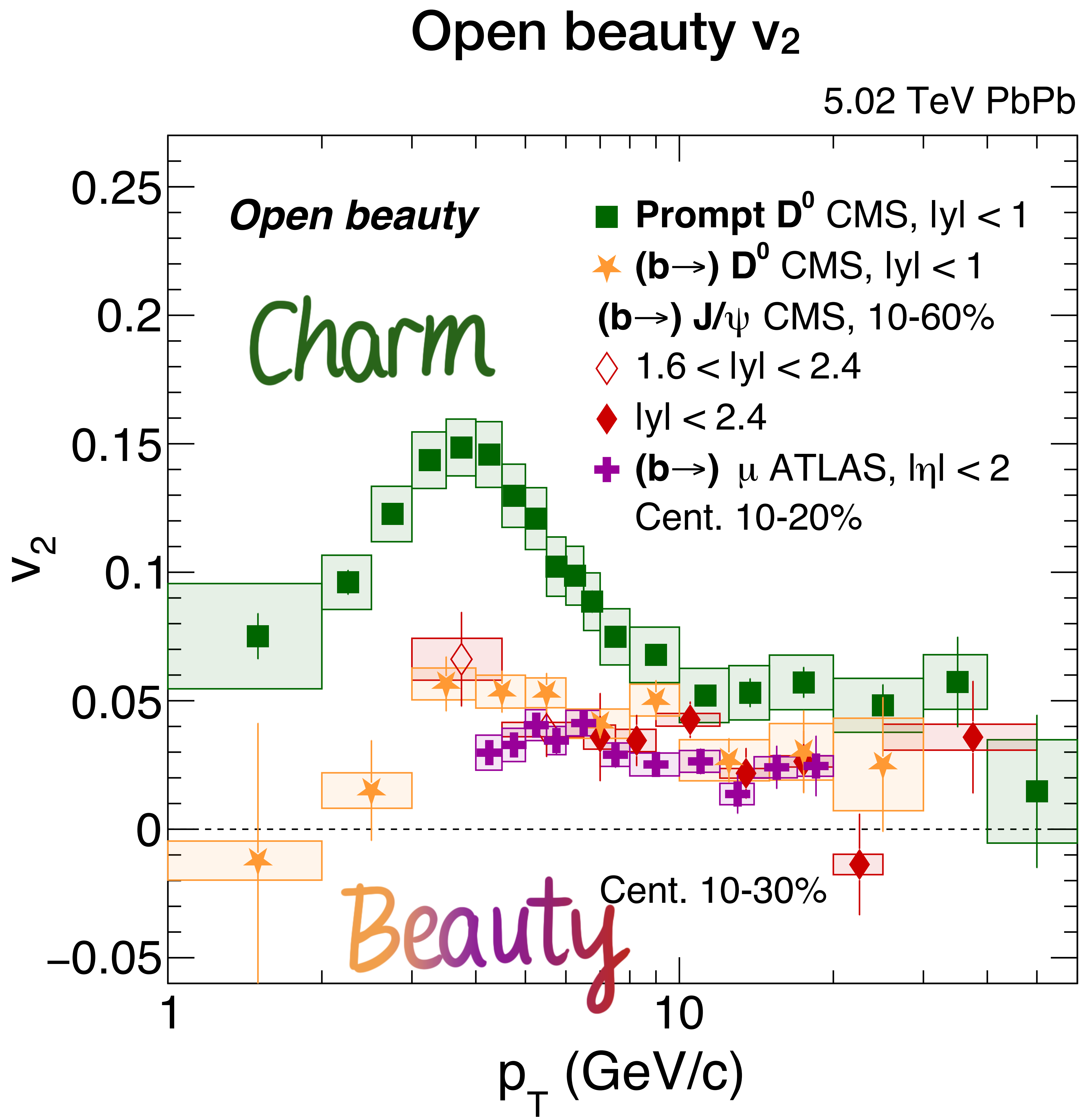
Charmonium v_2: J/ψ vs. ψ(2S)



- Hint of larger ψ(2S) v_2 than J/ψ v_2
  - Interplay of recombination and different suppression?

JHEP 10 (2020) 141
CMS-PAS-HIN-21-008

Open Beauty v_2 at LHC



- Open beauty v_2 is also well-established
  - Smaller than open charm v_2 at low p_T
  - All flavors tend to converge at high p_T

- *What about RHIC?*

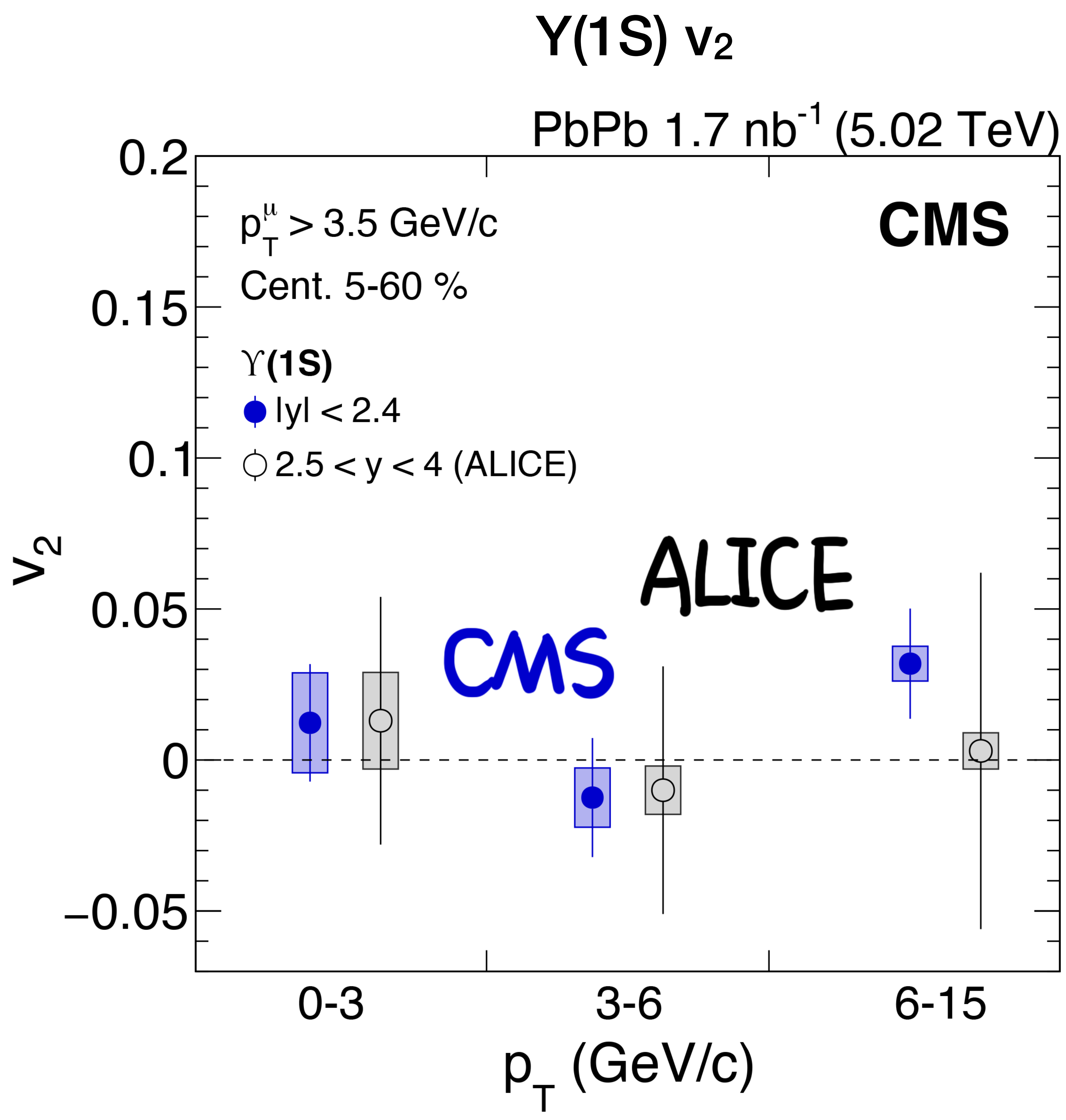
PLB 816 (2021) 136253

PLB 807 (2020) 135595

CMS-PAS-HIN-21-003

CMS-PAS-HIN-21-008

Bottomonium v_2 at LHC



- Bottomium flow not yet observed
- Open beauty pick up v_2 from light quark?
  - but recombination of B should be small?
- *Should Y suppression lead to asymmetry?*

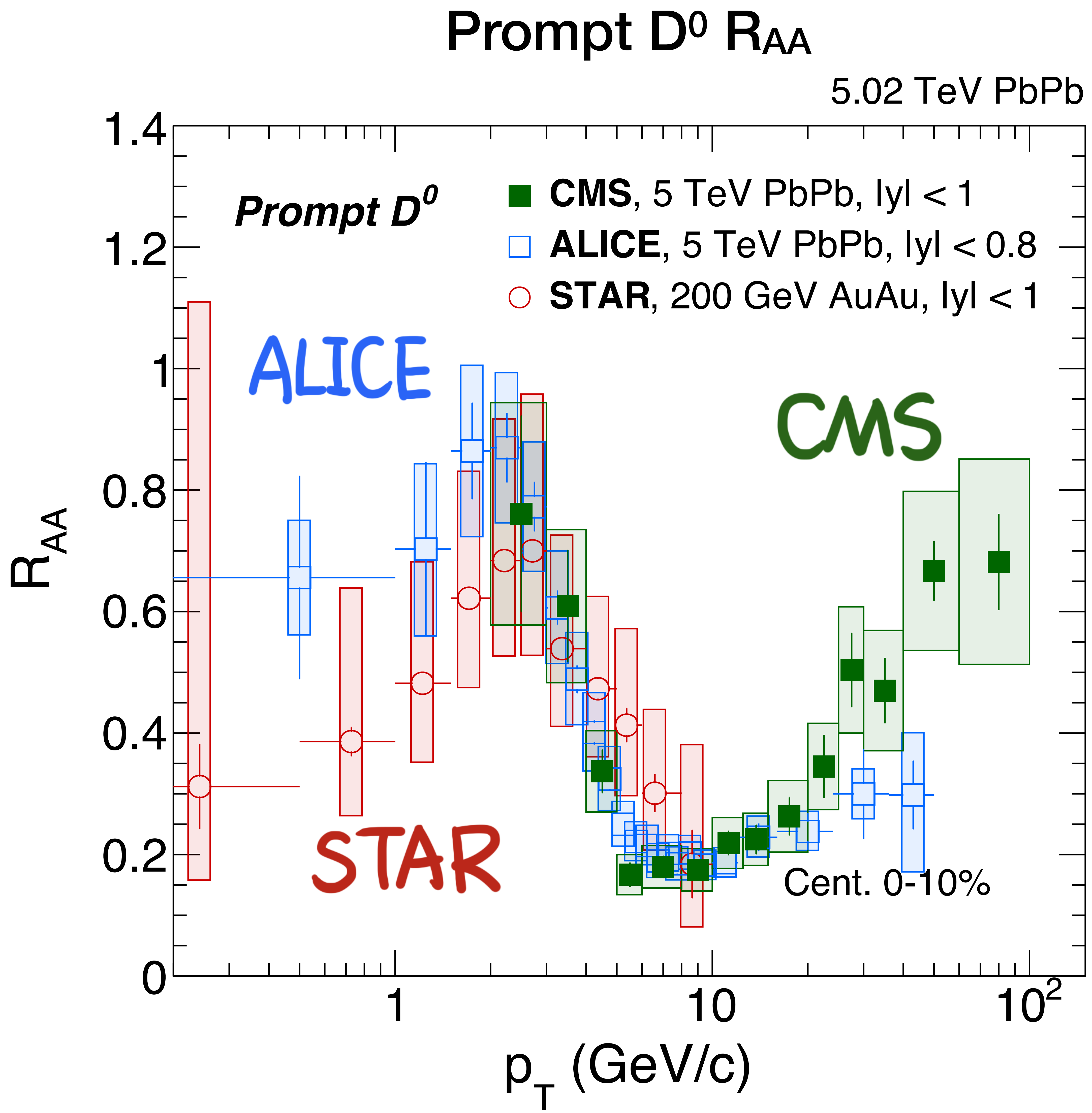
PLB 819 (2021) 136385

PRL 123 (2019) 192301

Section II.(II)

Heavy Flavor Energy Loss

Charm Energy Loss: Prompt D^0 R_{AA}



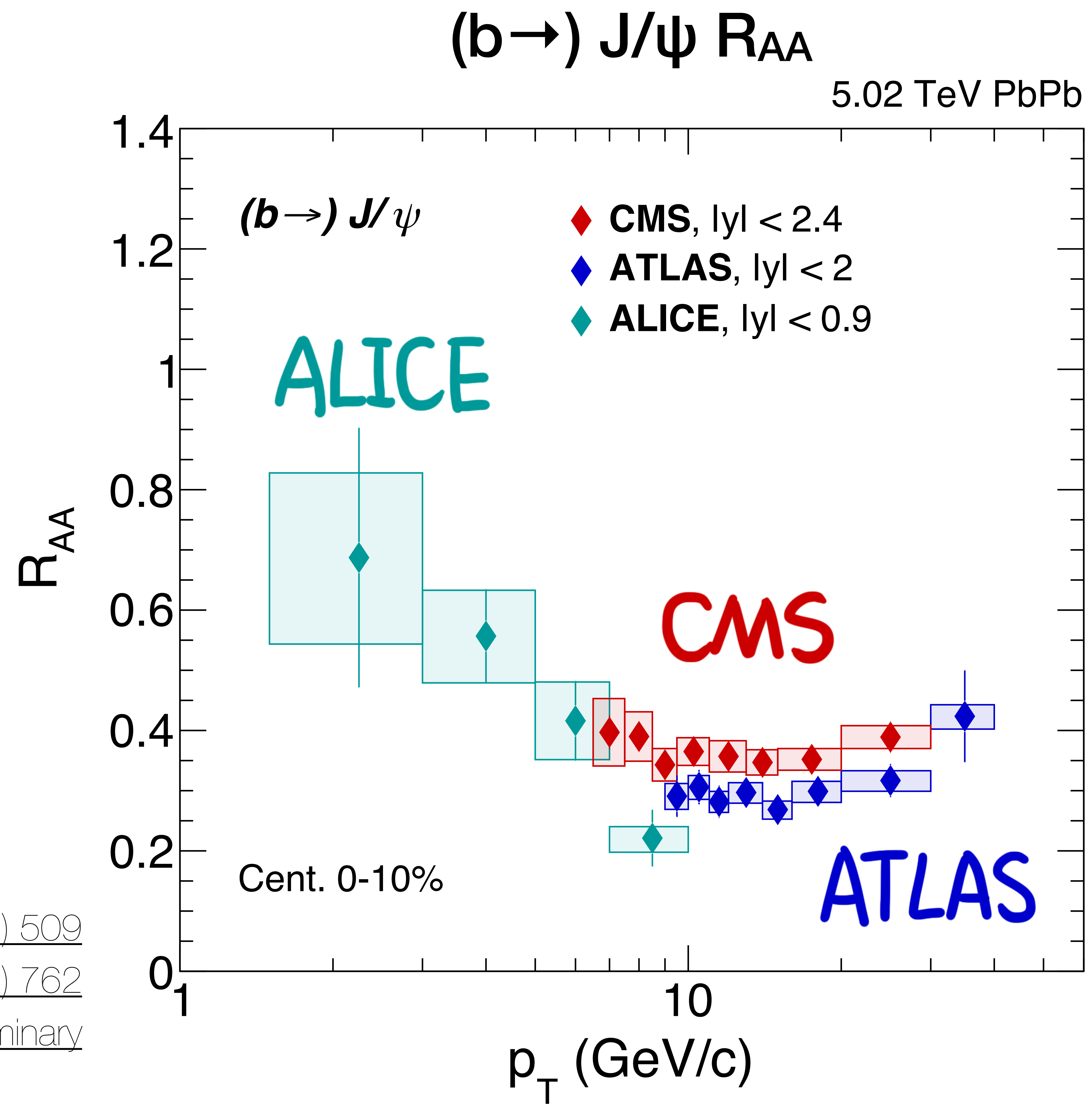
- *Similar D^0 R_{AA} in LHC and RHIC?*
  - Need better precision
  - High quality pp sample is important

PLB 782 (2018) 474

JHEP 01 (2022) 174

PRC 99 (2019) 034908

Beauty Energy Loss at LHC

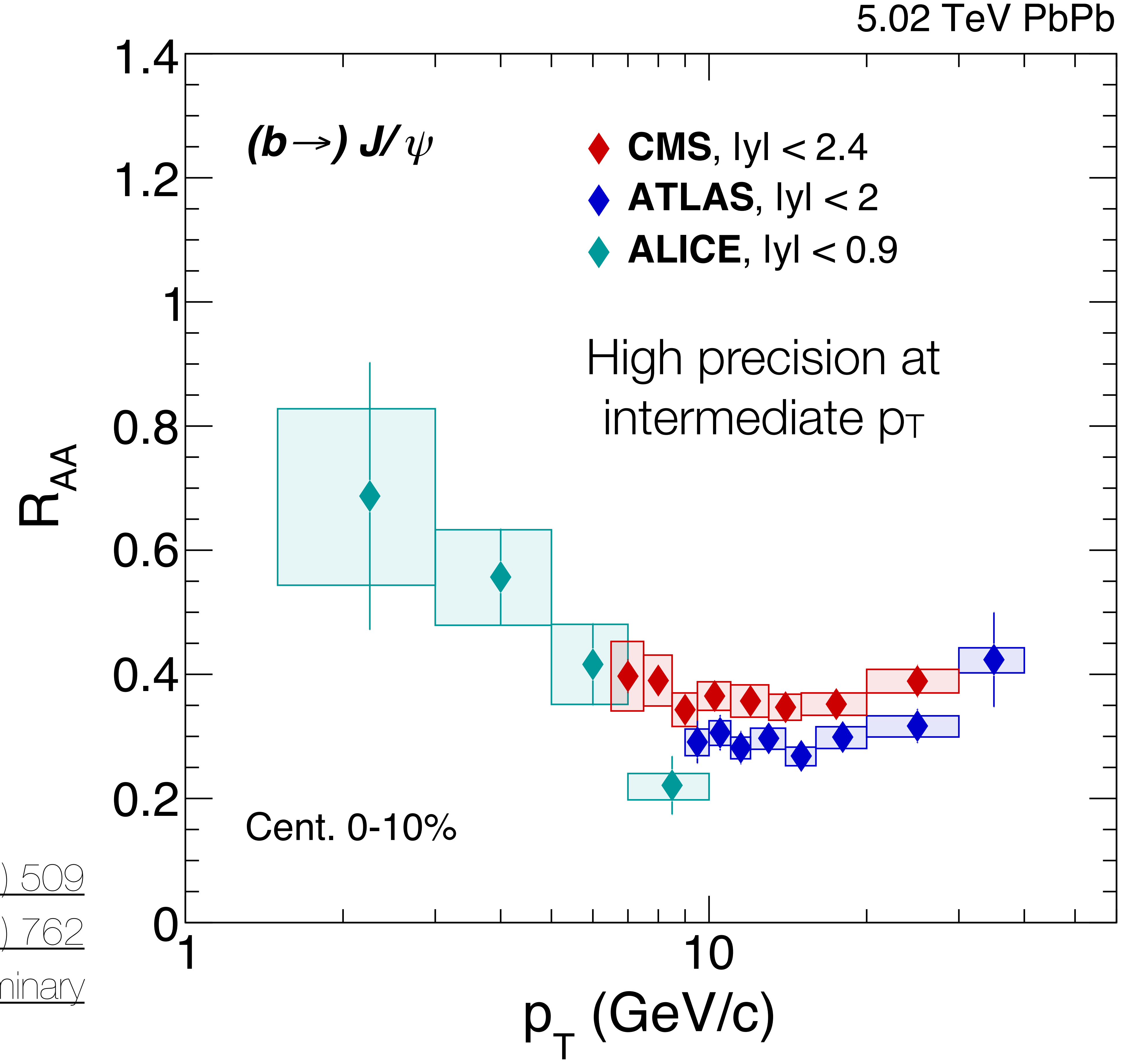


EPJC 78 (2018) 509
EPJC 78 (2018) 762
ALICE Preliminary

- Little inconsistency between CMS and ATLAS ➜ should follow it up

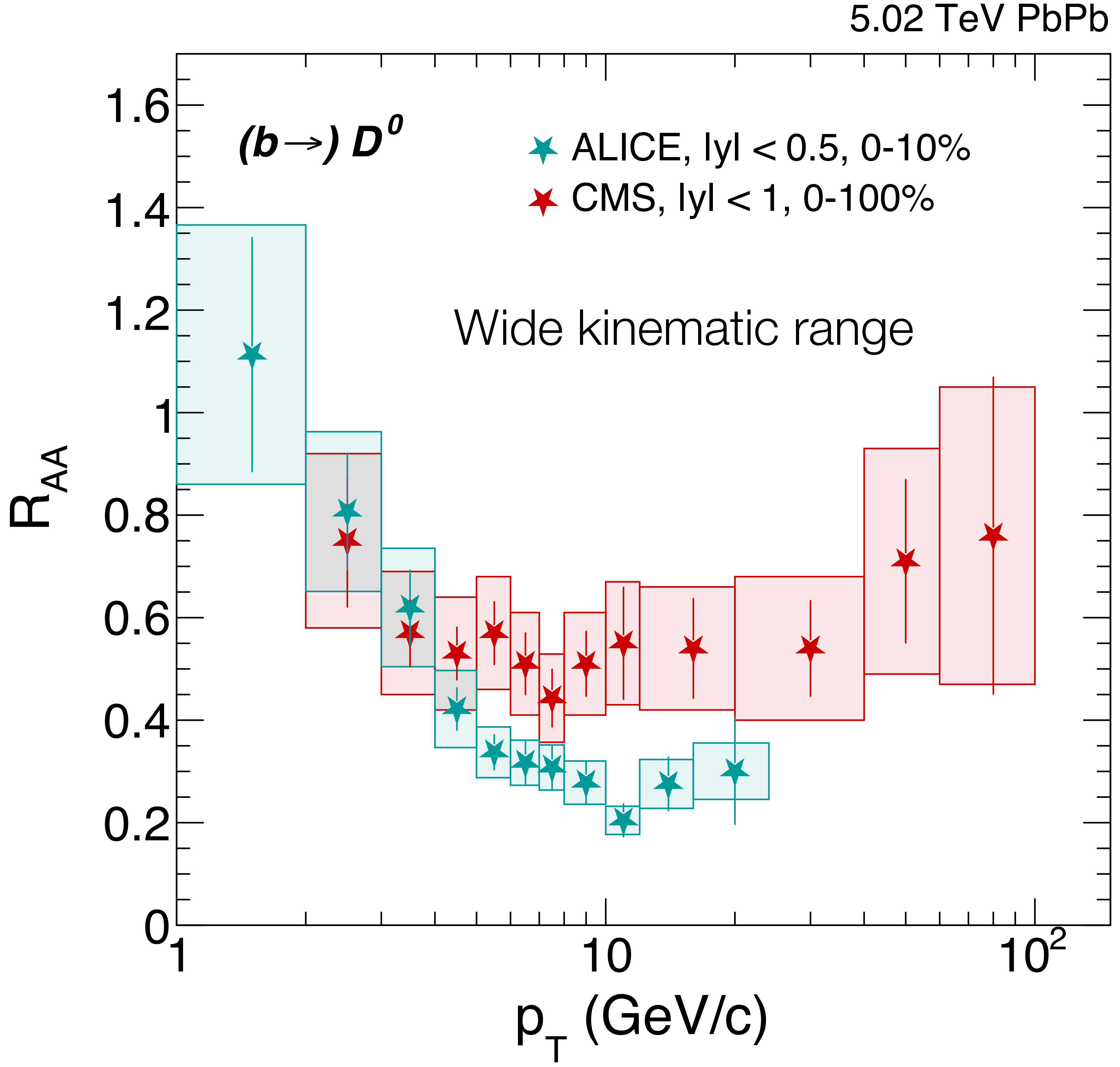
Beauty Energy Loss at LHC

(b→) J/ψ R_{AA}



EPJC 78 (2018) 509
EPJC 78 (2018) 762
ALICE Preliminary

(b→) D^0 R_{AA}

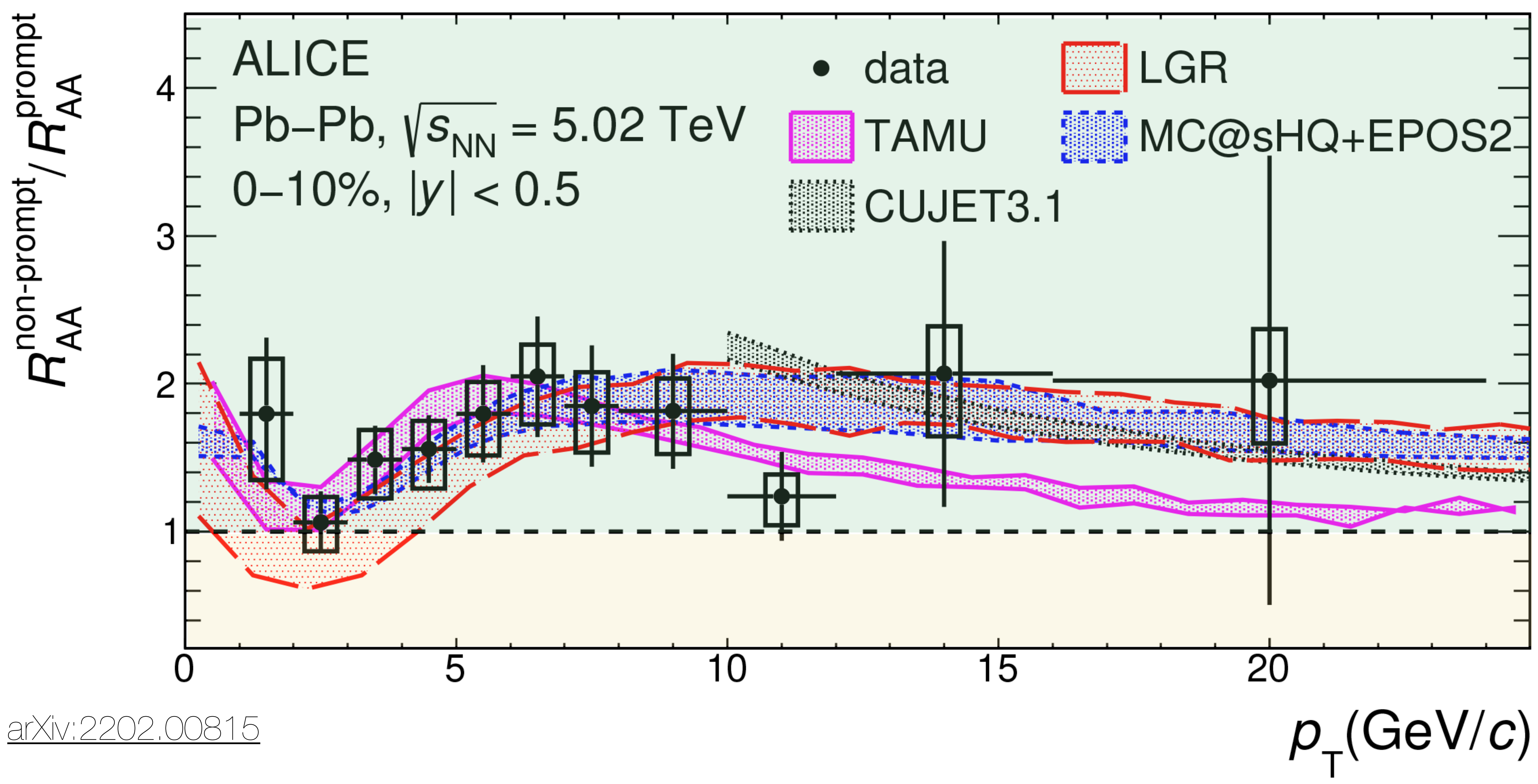


arXiv:2202.00815
PRL 123 (2019) 02200

- Only beauty decay lepton R_{AA} measured at RHIC ➜ *(b→) D^0 R_{AA} in sPHENIX*
- Kinematics of hadron daughters are closer to the parents than leptons

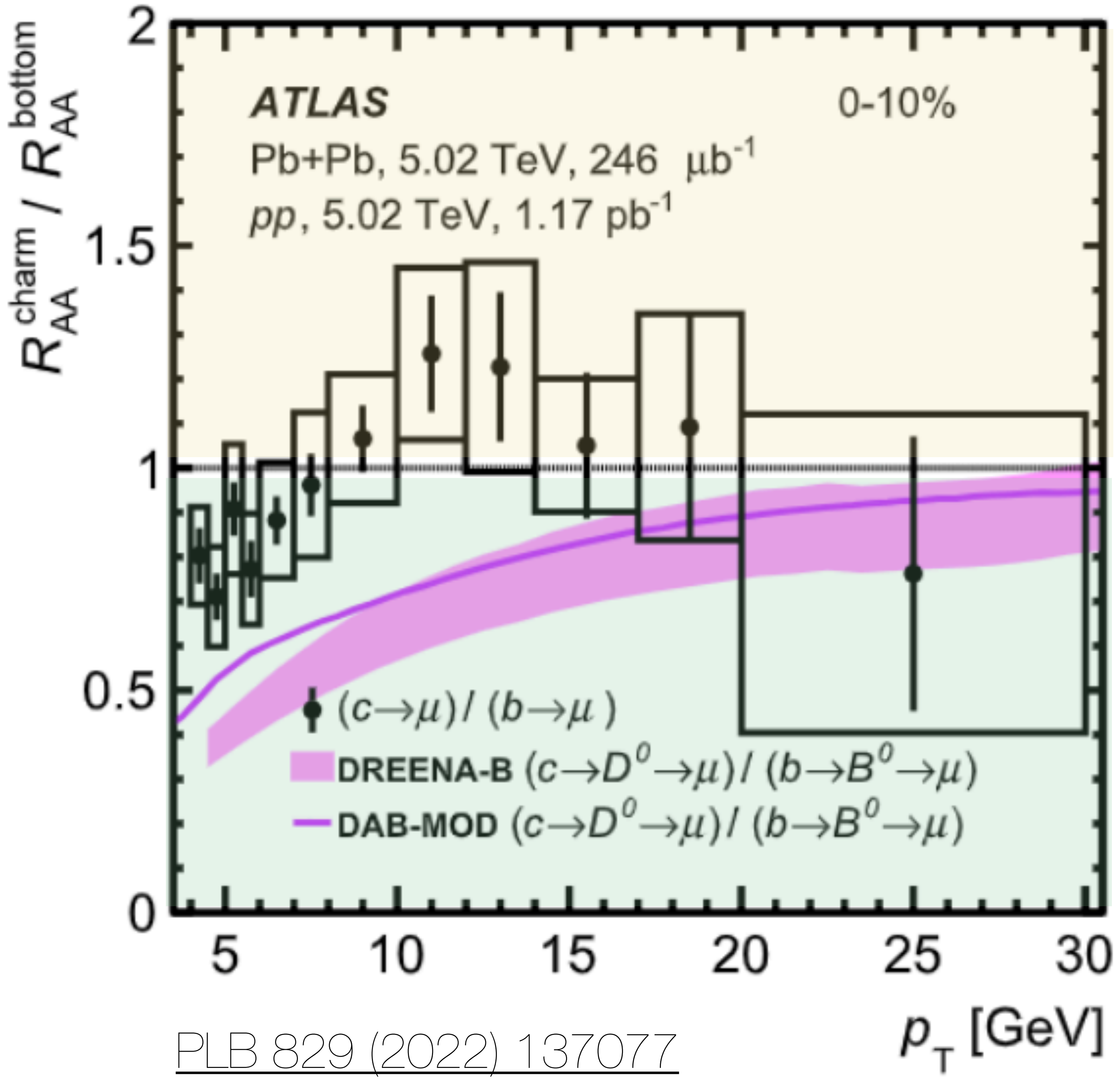
Flavor Dependence of R_{AA}

b→D⁰ / Prompt D⁰ R_{AA}



arXiv:2202.00815

c→μ / b→μ R_{AA}



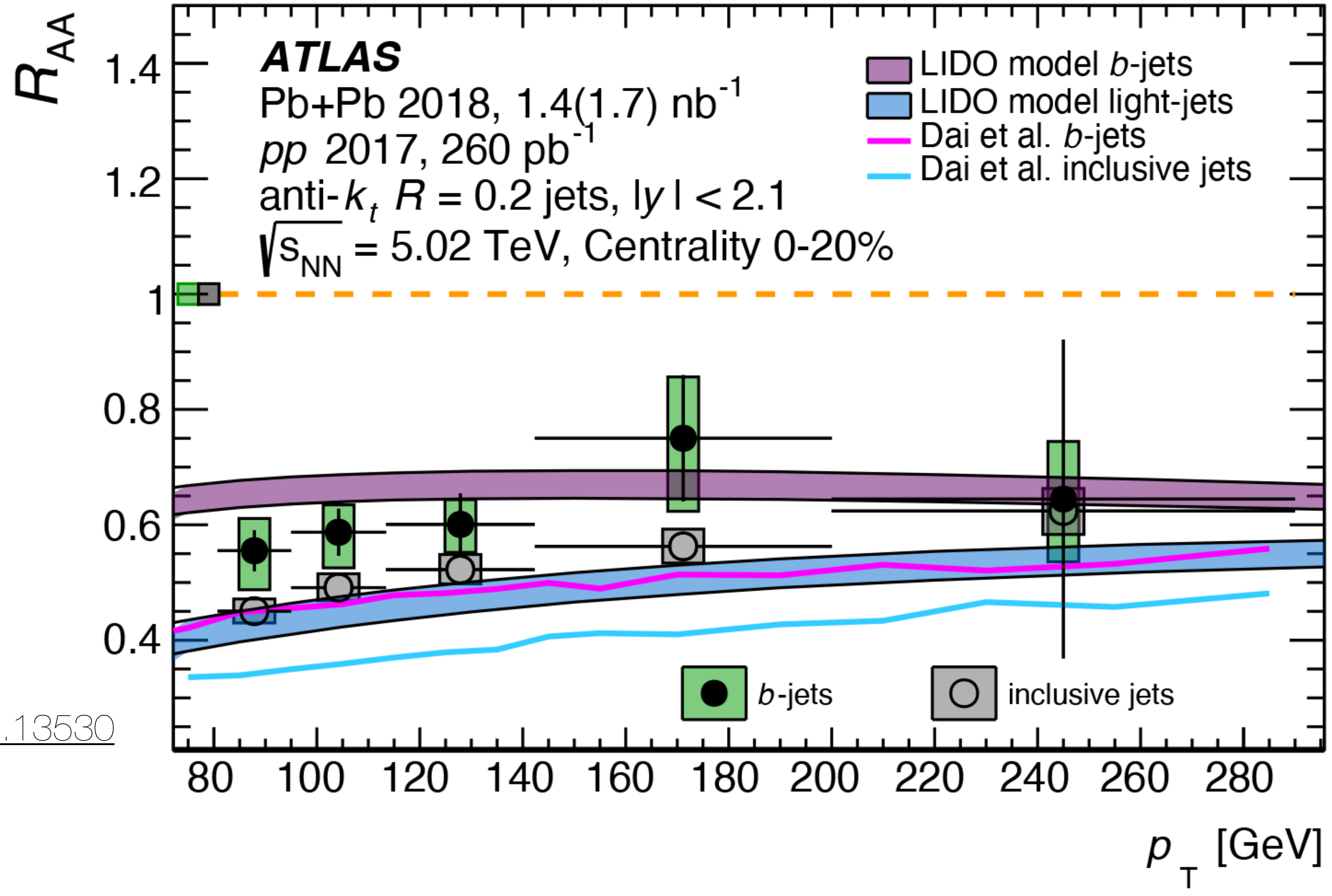
PLB 829 (2022) 137077

- ALICE: R_{AA}(b→D⁰) > R_{AA}(Prompt D⁰) over full p_T
- Interplay of energy loss, shadowing, flow, coalescence, spectrum shapes, …

- ATLAS: R_{AA}(b→μ) < R_{AA}(c→μ) in part of p_T ranges
  - Not predicted by theory
  - Not observed at RHIC

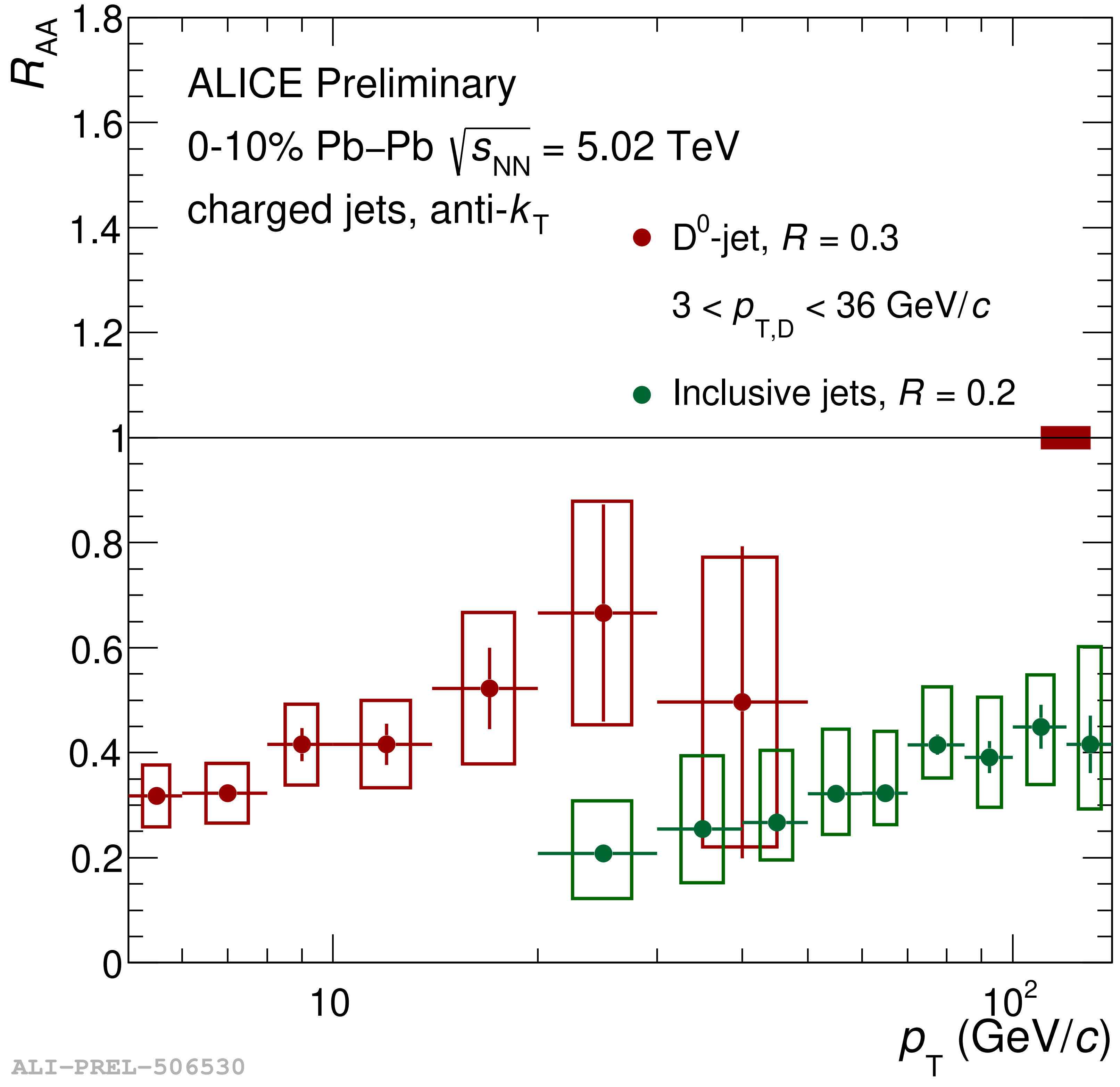
Heavy Flavor Jet R_{AA}

b-jet R_{AA}



arXiv:2204.13530

D^0 tagged jet R_{AA}

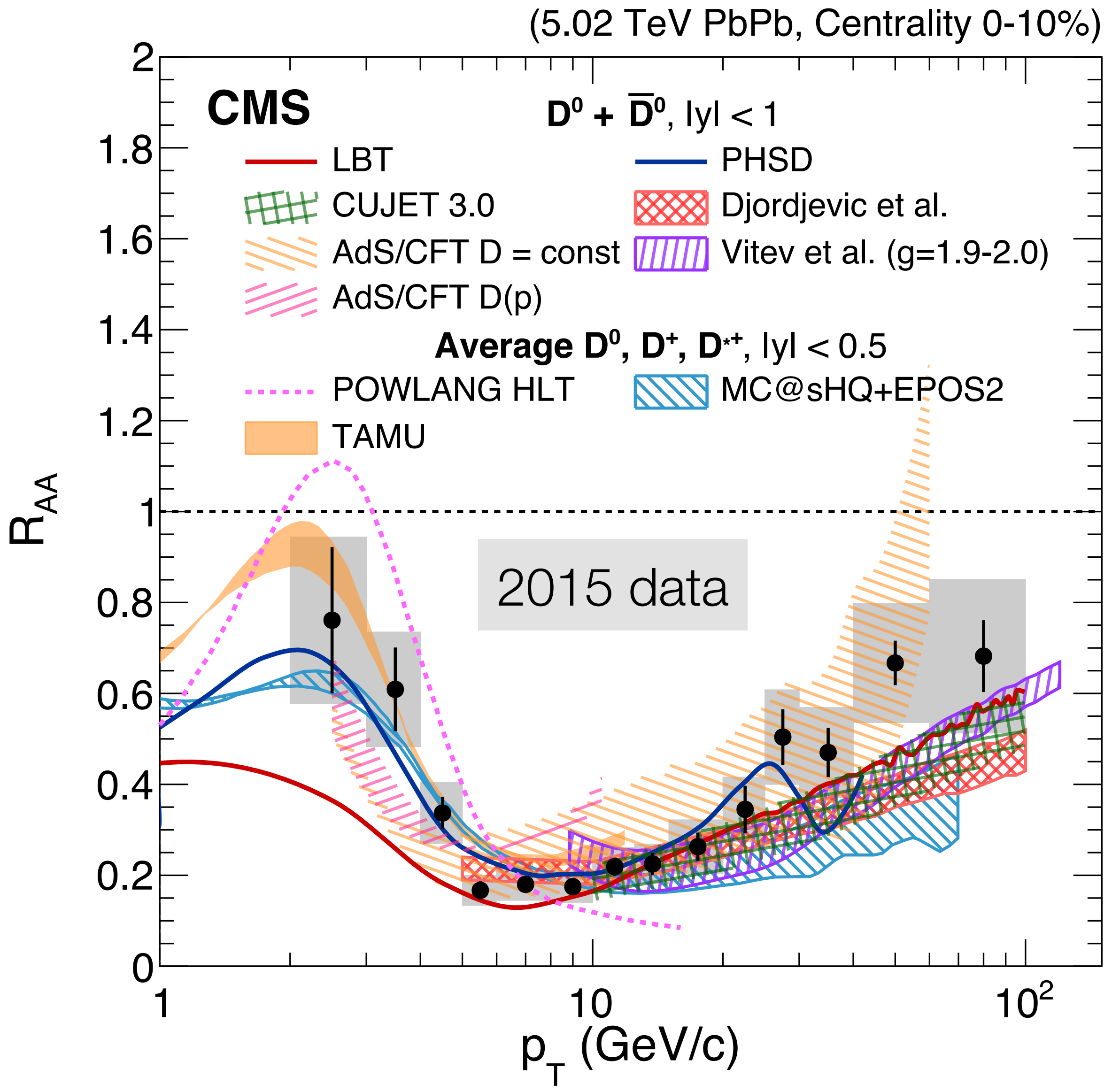


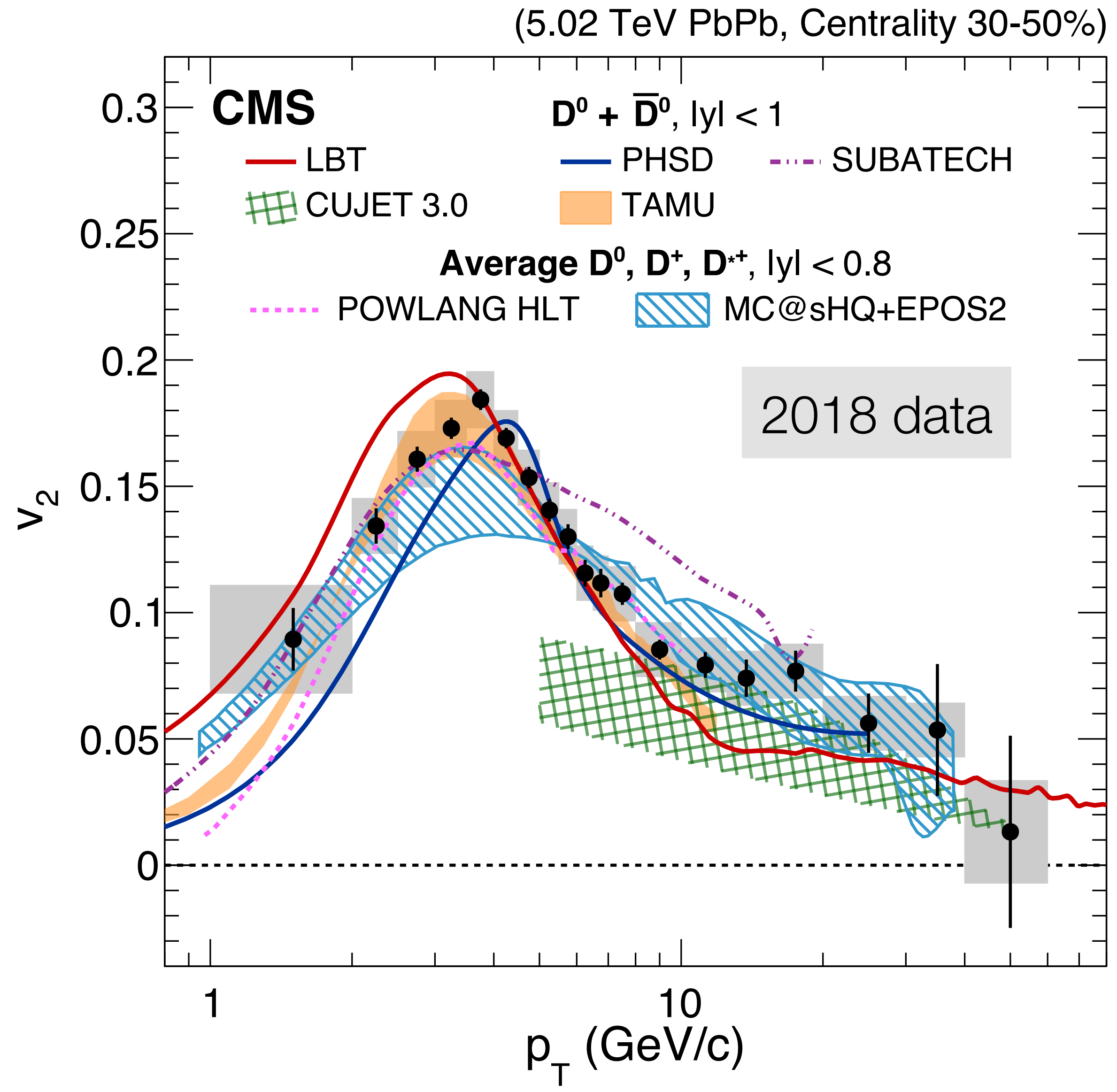
- Less suppression for b-jet (D^0 tagged jet) than inclusive jets
  - Quark jet vs. gluon jet
- *HF jet down to very low p_T*: Study energy loss not sensitive to hadronization

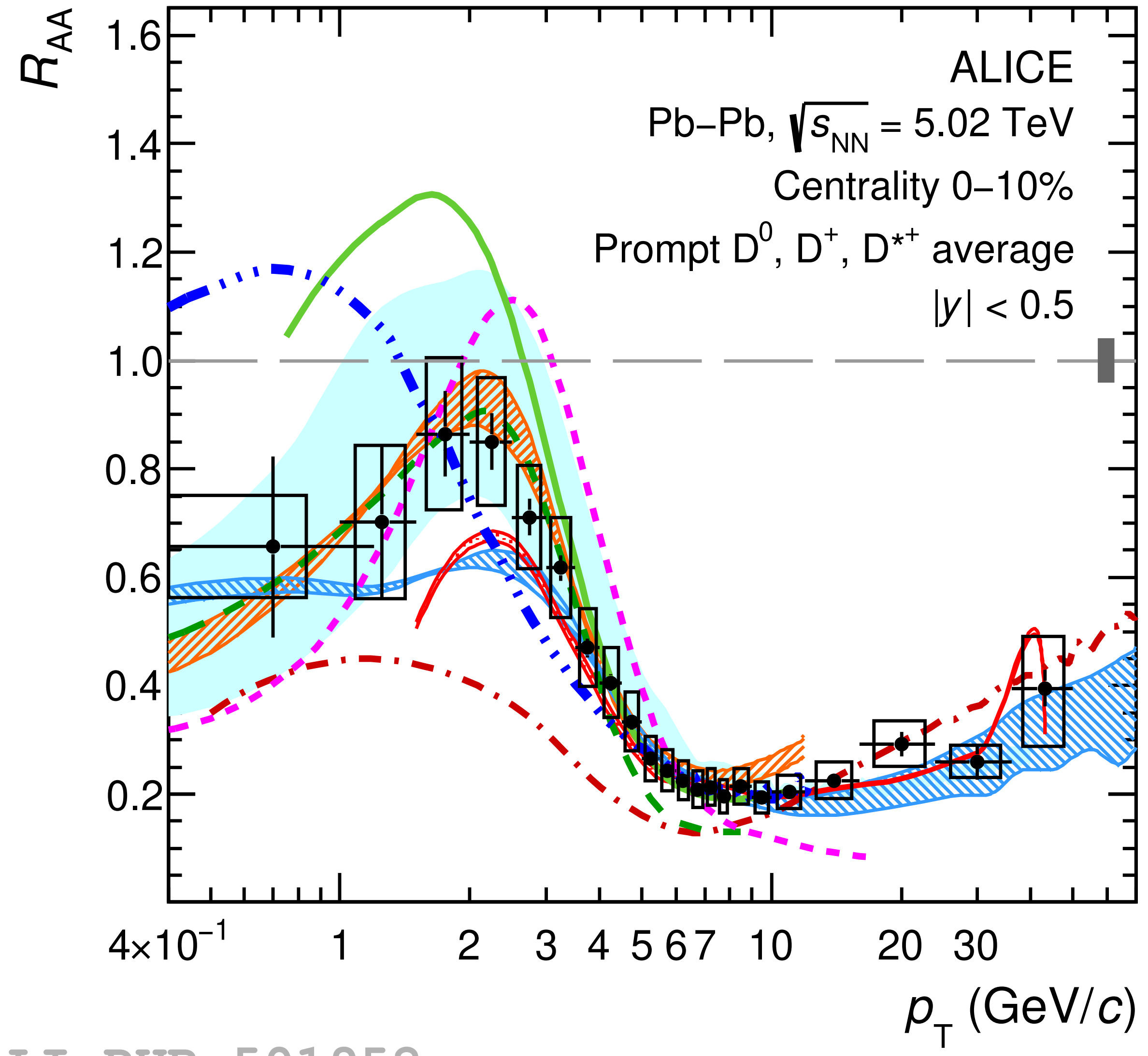
Section II.(III)

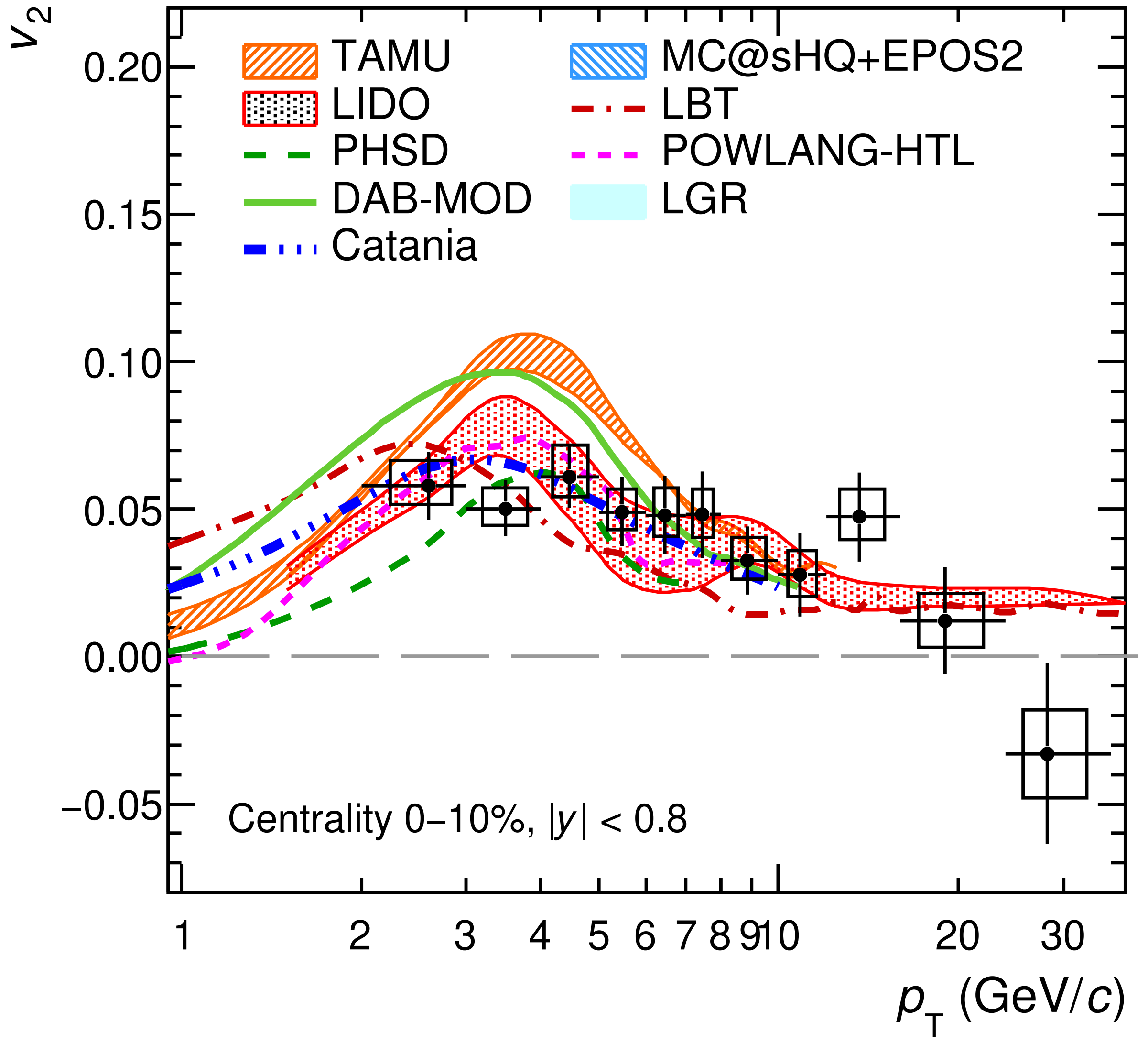
Quick Discussion on R_{AA} and v_2

Model Comparison







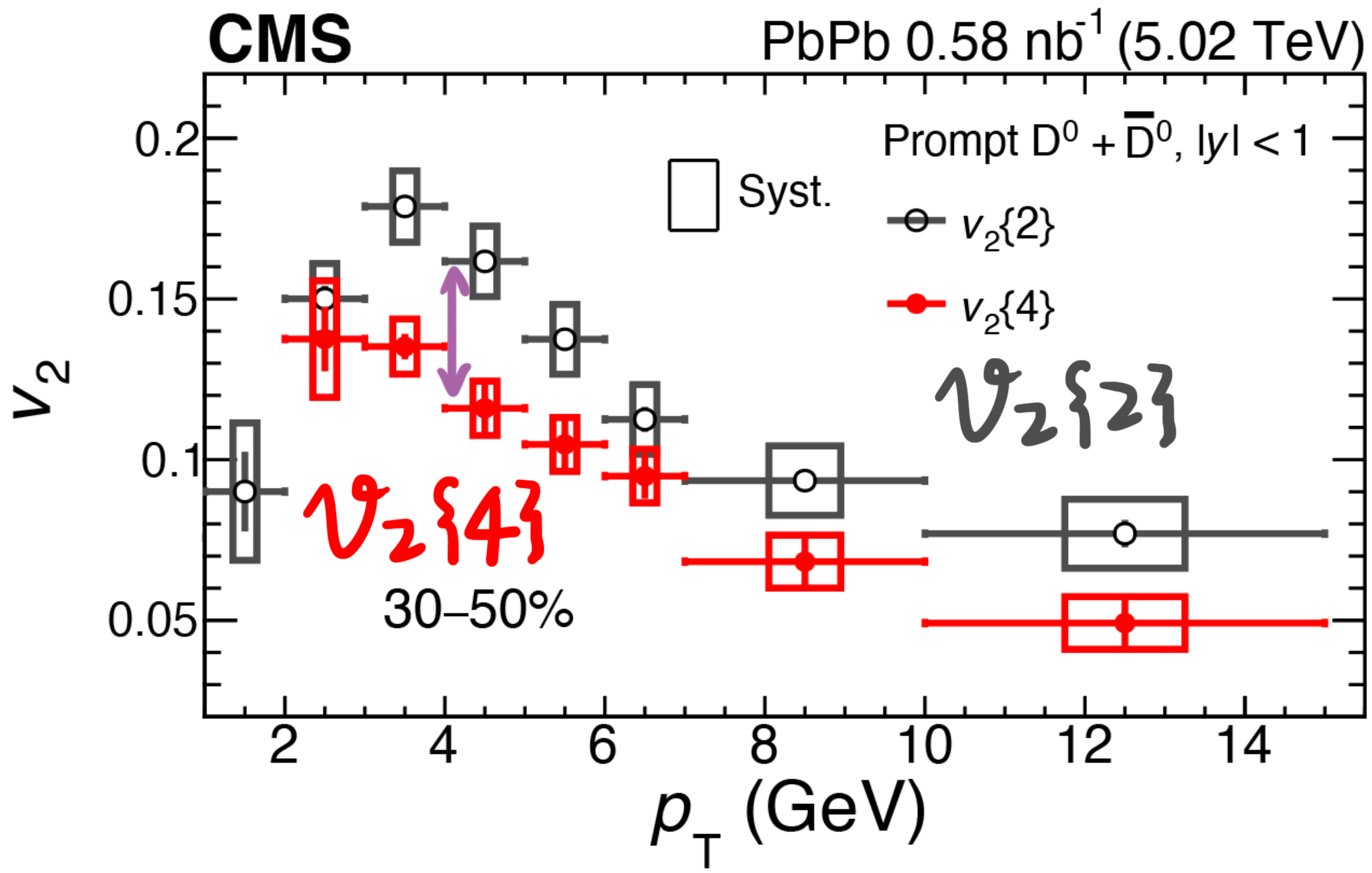


ALI-PUB-501952

- Data described by many models fairly well
  - Data significantly constrained models
  - Or actually "overtrained" the models…
    - ➡Very different underlying mechanisms and components in these models
- *sPHENIX result will be a good test*
  - Different collision systems and energies
  - More divergent at low p_T
- But only improving precision is probably not enough…
  - New observables than the traditional ones

New Observable: Multi-particle Correlation

Prompt D^0 $v_2\{2\}$ vs. $v_2\{4\}$



PRL 129 (2022) 022001

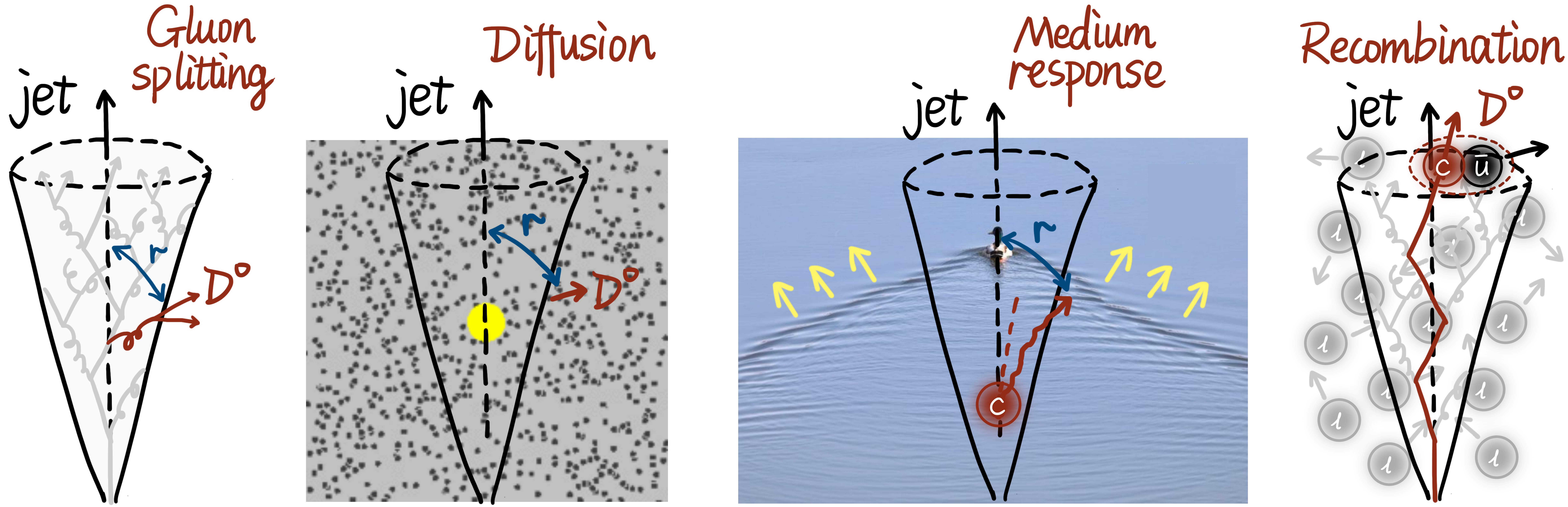
- Probe event-by-event fluctuation
  - $v_2\{2\}^2 \approx \boxed{\langle v \rangle^2} + \boxed{\sigma^2}$
  - $v_2\{4\}^2 \approx \boxed{\langle v \rangle^2} - \boxed{\sigma^2}$

  flow fluctuation

- Indeed $v_2\{4\} < v_2\{2\}$ for D^0
  - Provide additional constraints

- Fluctuations from both initial geometry (soft) and energy loss (hard)
  - can be distinguished by p_T dependence of $v_2\{4\}/v_2\{2\}$

New Observable: Correlation with Hard Probe

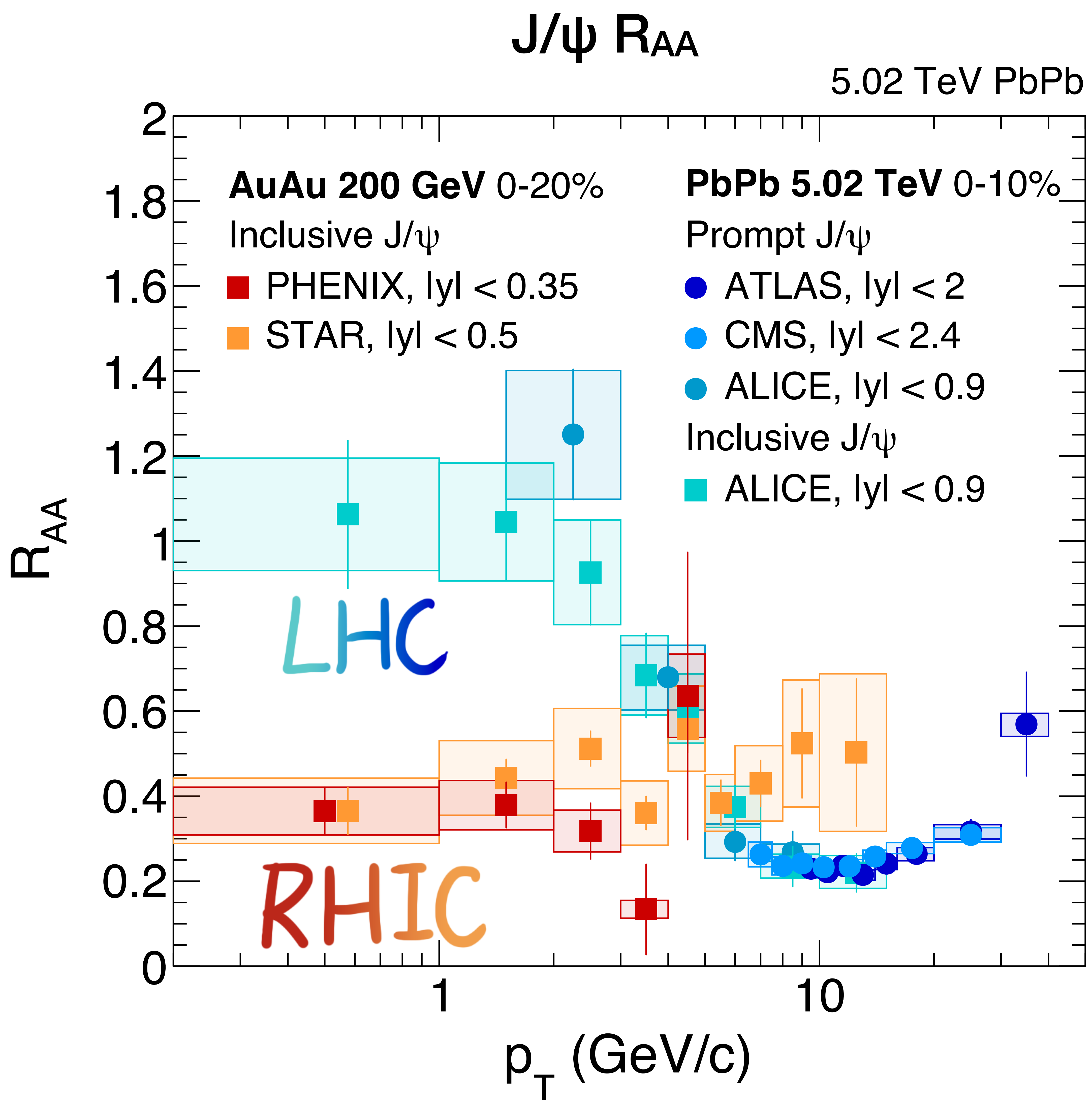


- New constraints of diffusion with a hard reference: jet-D, photon-D, h-D, …
- Study effects that decouple charm and axis

Section II.(IV)

Quarkonium Production

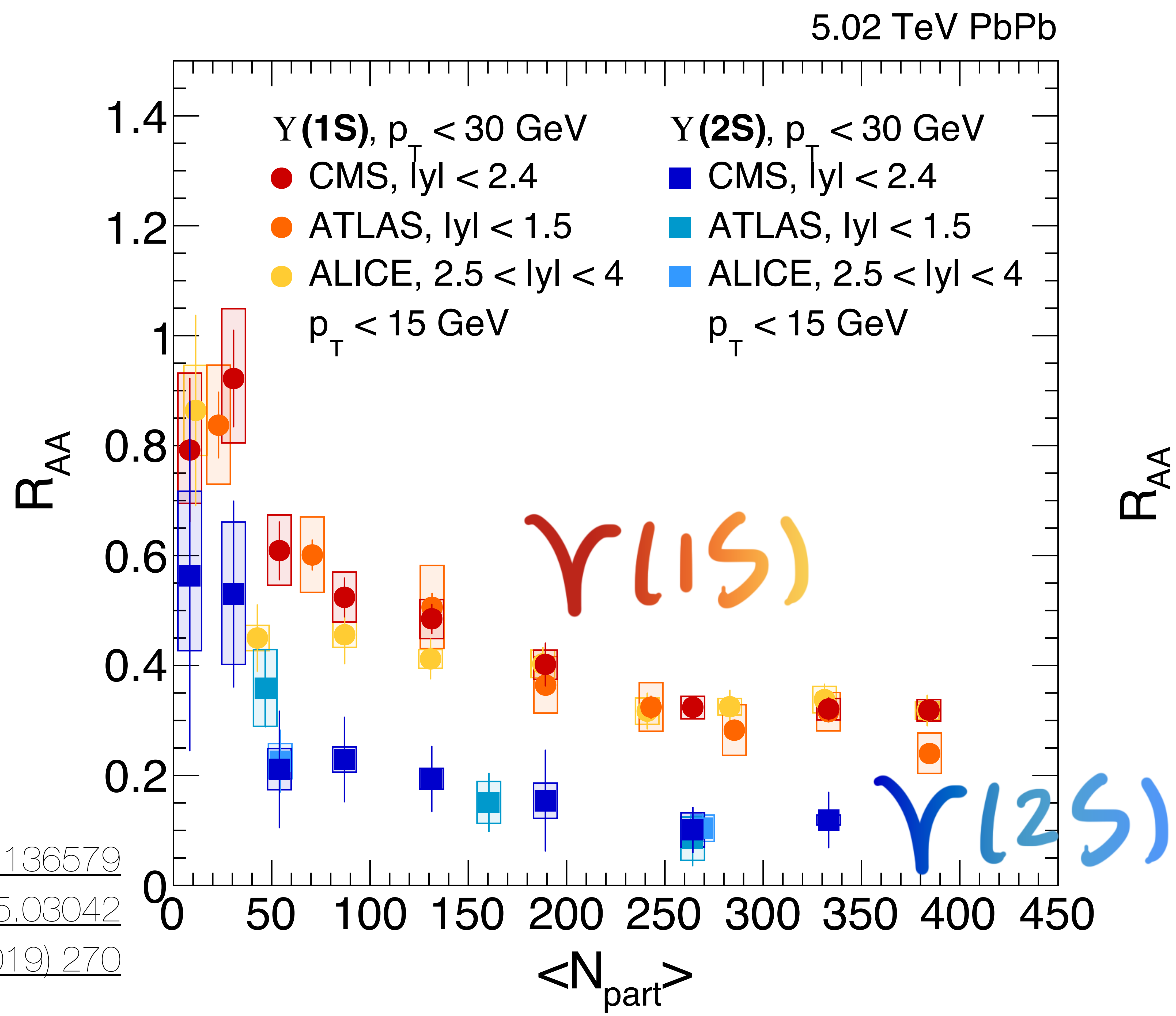
J/ψ Production in Heavy-ion Collisions

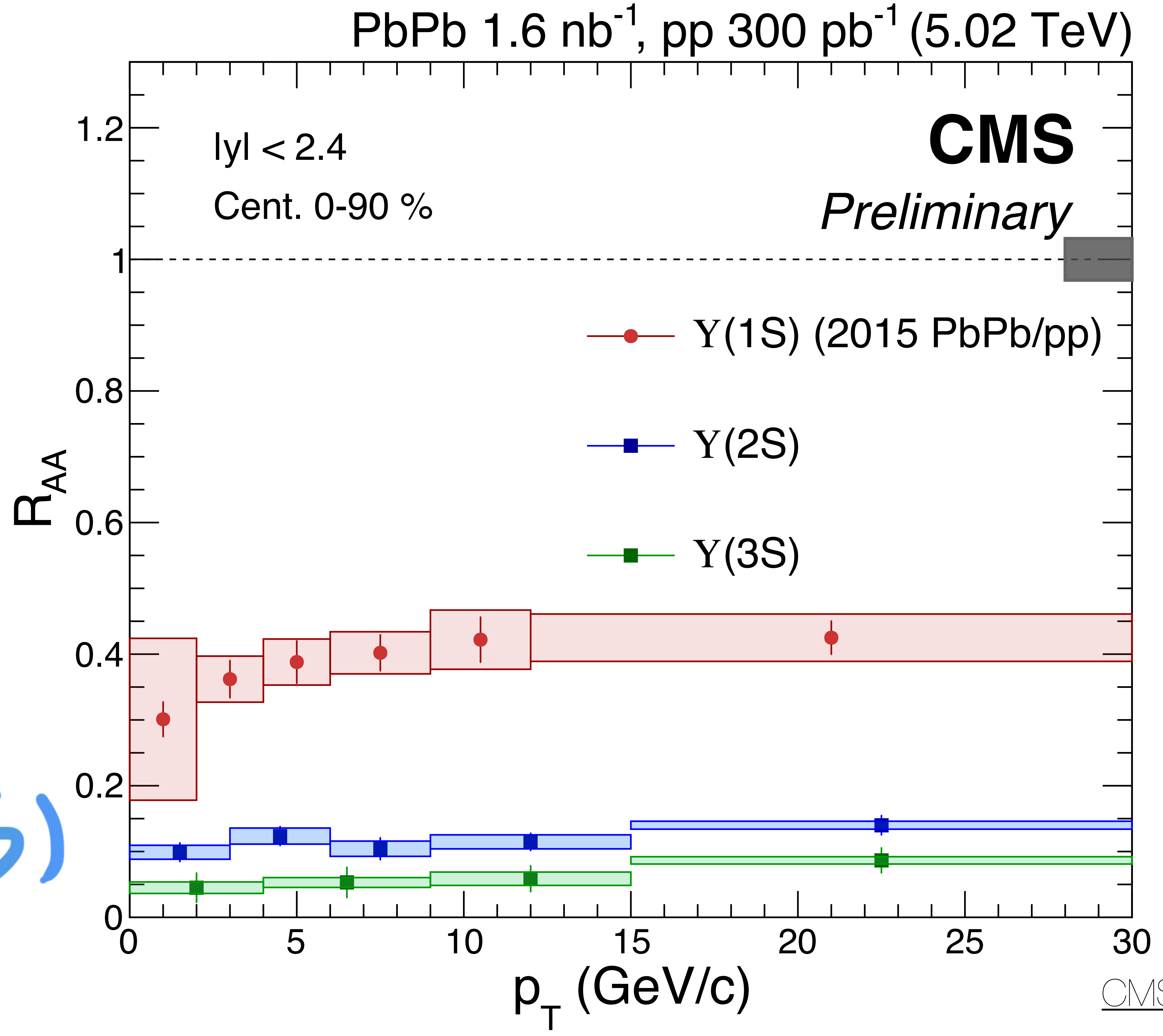


- Different J/ψ behavior at LHC and RHIC (both R_{AA} and v_2)
  - Enhancement at low p_T as a sign of recombination
    ➡ LHC has larger $\sigma_{c\bar{c}}$
  - Constrain different components with both LHC and RHIC measurements

EPJC 78 (2018) 762
EPJC 78 (2018) 509
PRL 98 (2007) 232301
PLB 797 (2019) 134917

Υ Suppression in Heavy-ion Collisions





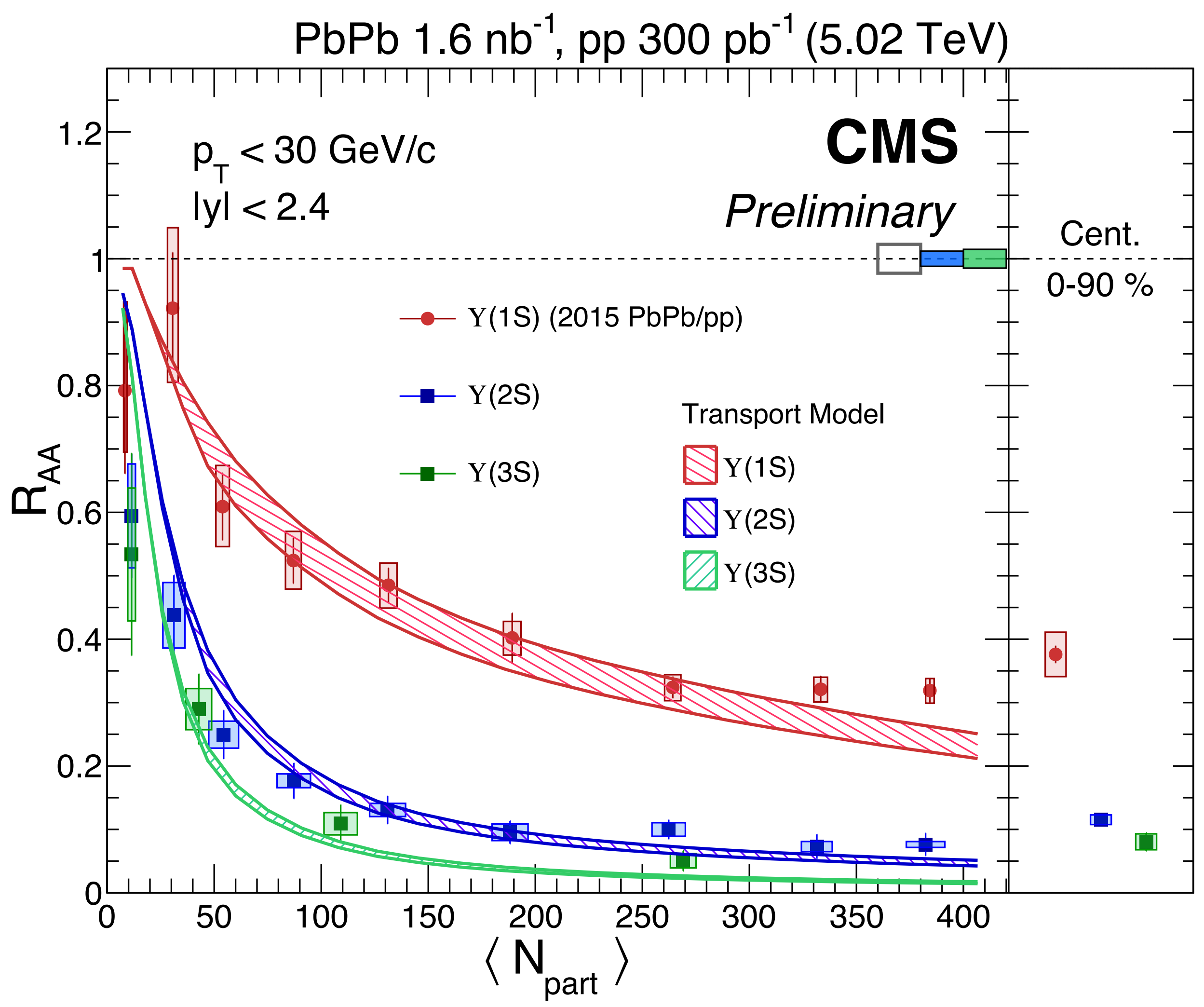
PLB 822 (2021) 136579
arXiv:2205.03042
PLB 790 (2019) 270

CMS-PAS-HIN-21-007

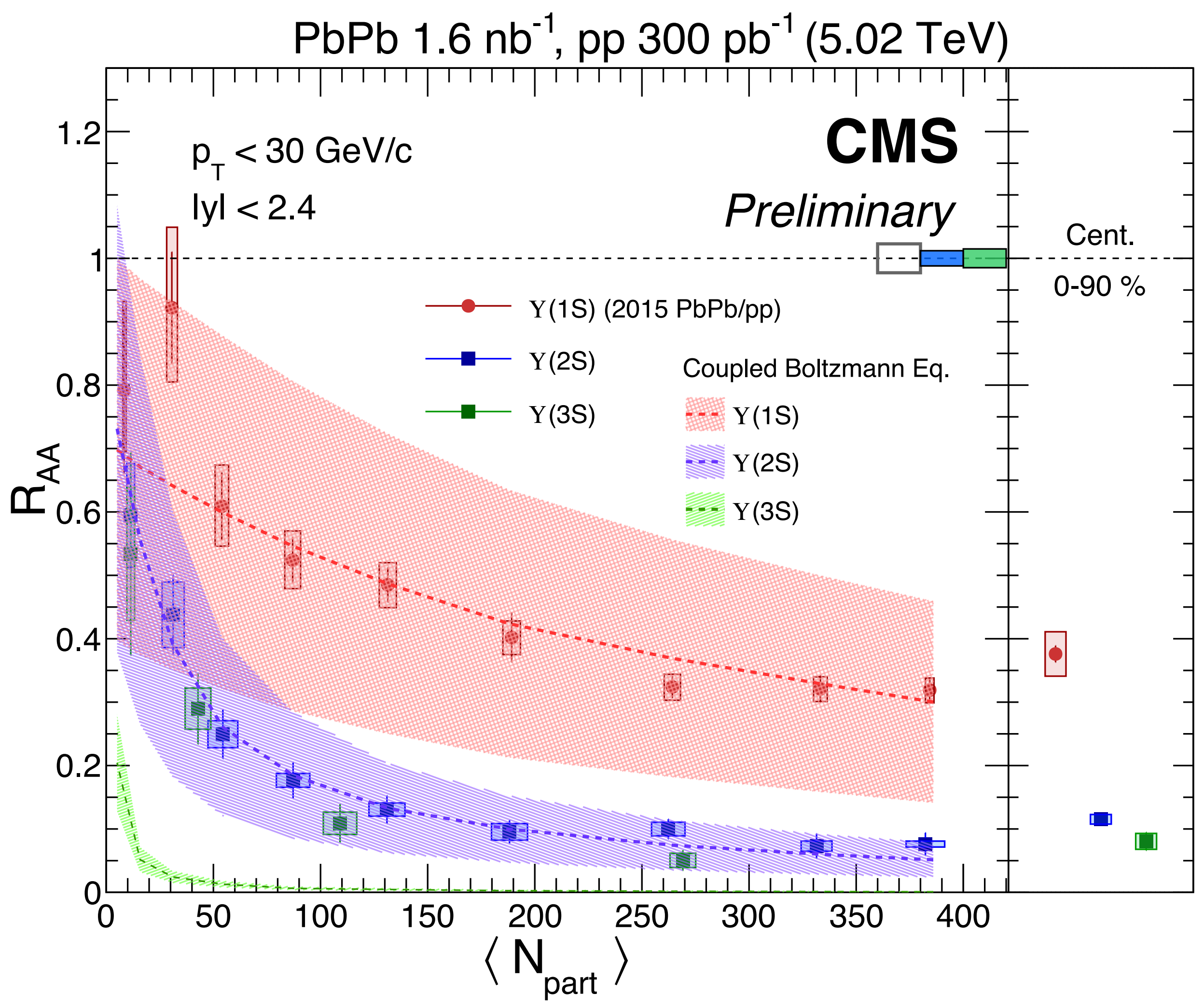
- Consistent Υ(1S), Υ(2S) results at LHC
- Υ(3S) stronger suppressed

Υ Suppression: Model Comparison (1/2)

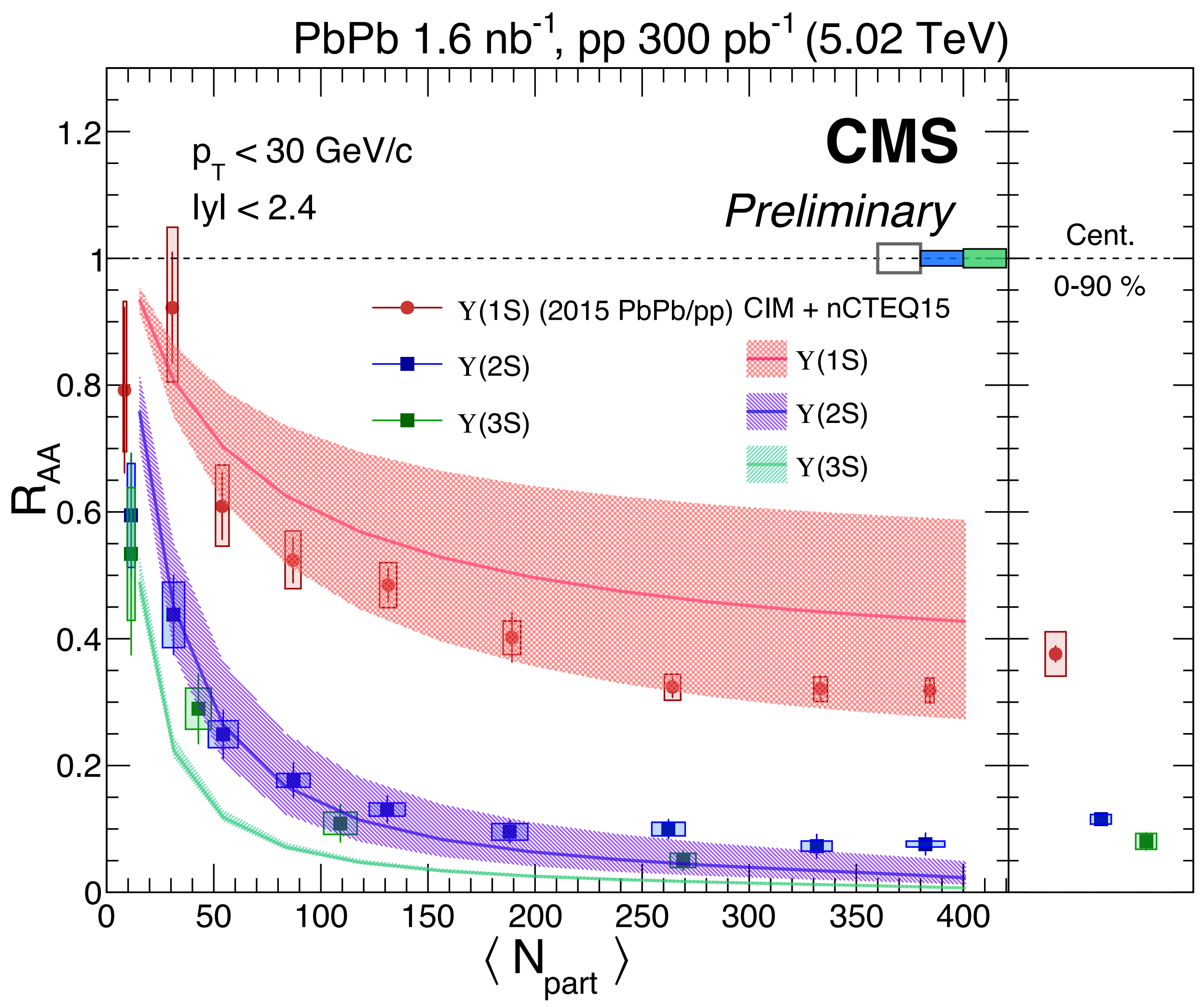
→ TAMU transport model
[PRC 96 (2017) 054901]



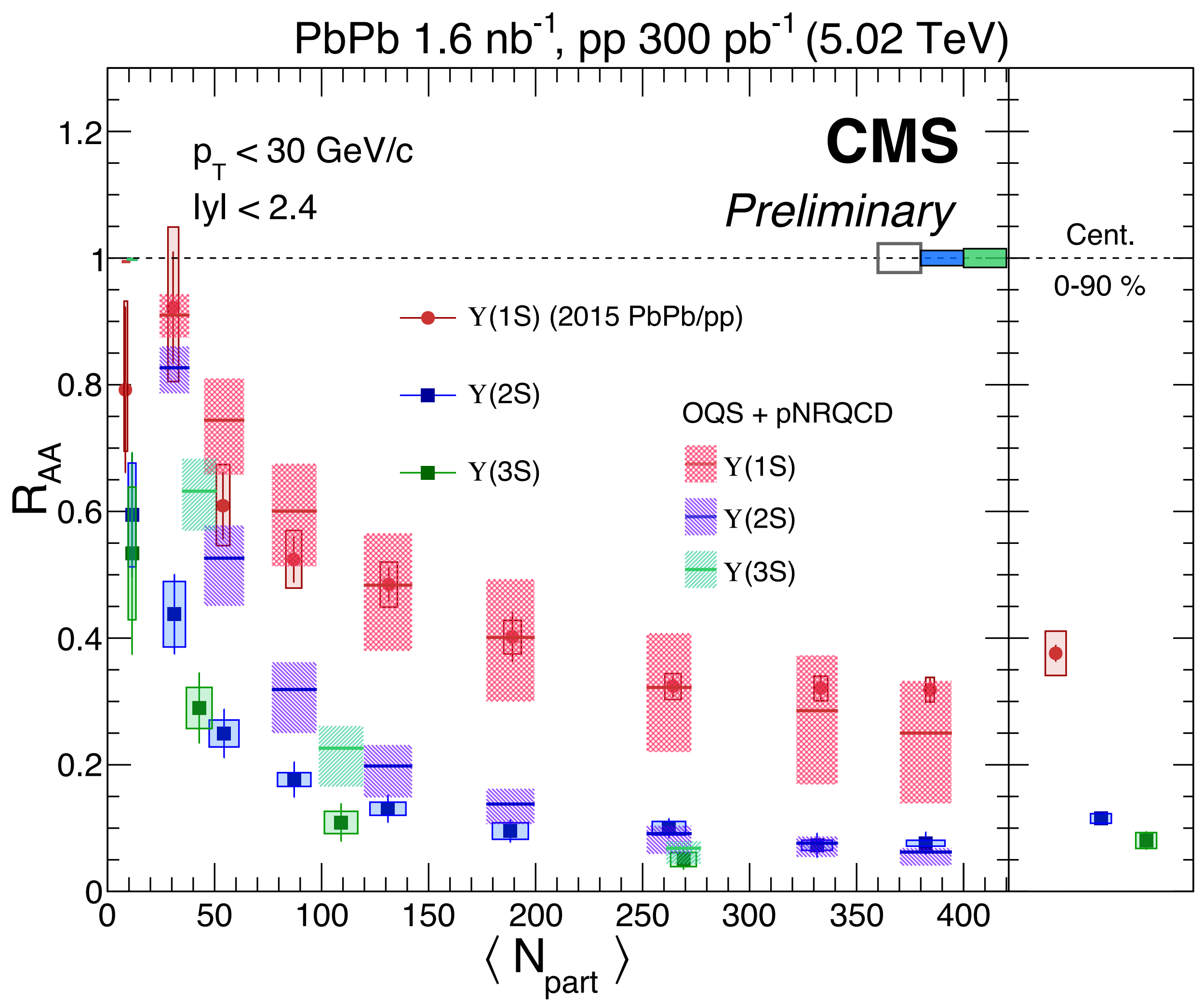
→ Coupled Boltzmann eq.
[JHEP 01 (2021) 046]



→ Comover interaction
[JHEP 10 (2018) 094]
No thermalization



→ Open-quantum system
+ pNRQCD
[PRD 104 (2021) 094049]



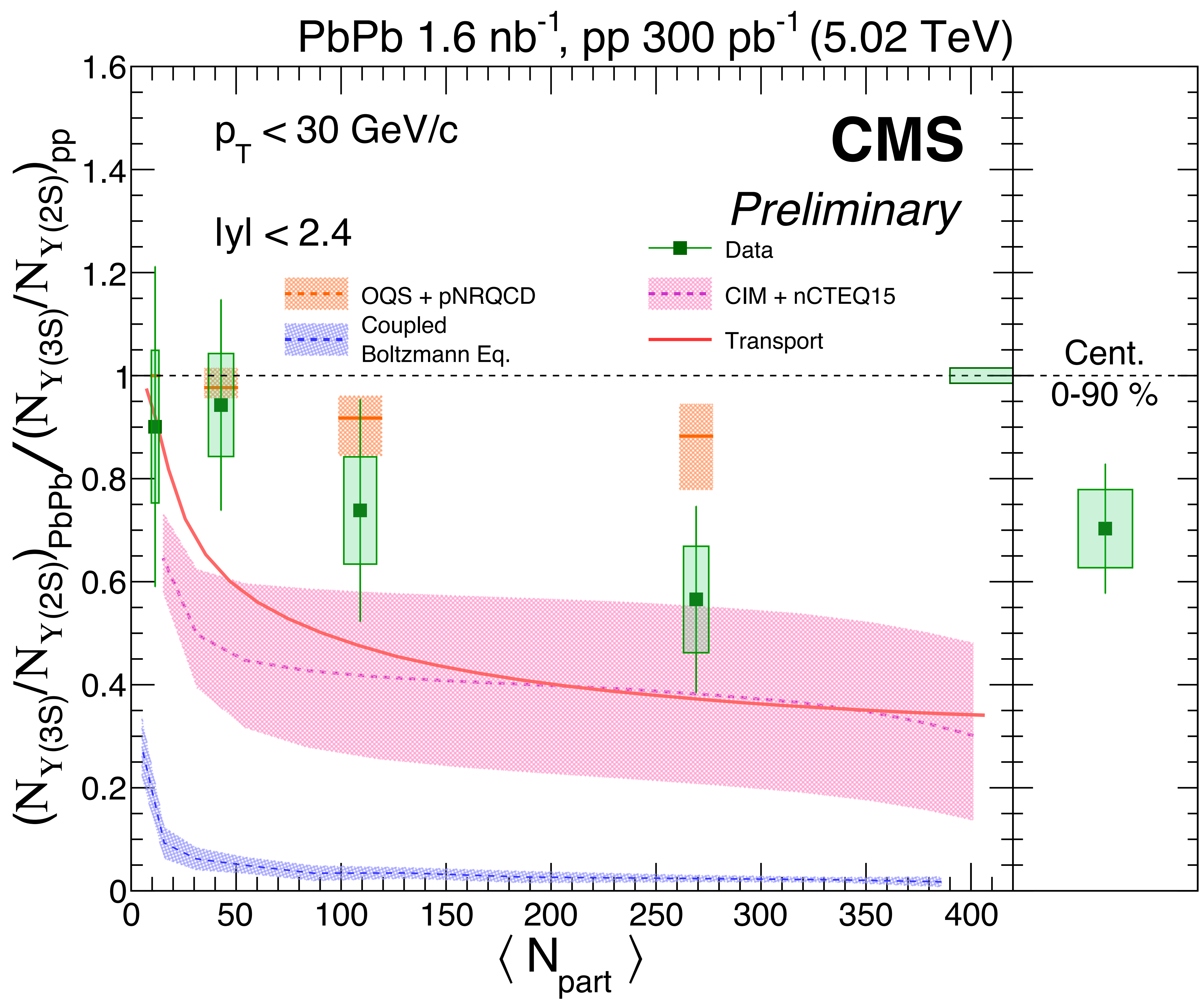
- Reasonable description of Υ(1S) and Υ(2S) data *with very different ingredients*
  - Different hydro simulation
  - With and without thermalization
- sPHENIX measurements at RHIC can provide another different constraint

Collected by Florian's talk

CMS-PAS-HIN-21-007

Υ Suppression: Model Comparison (2/2)

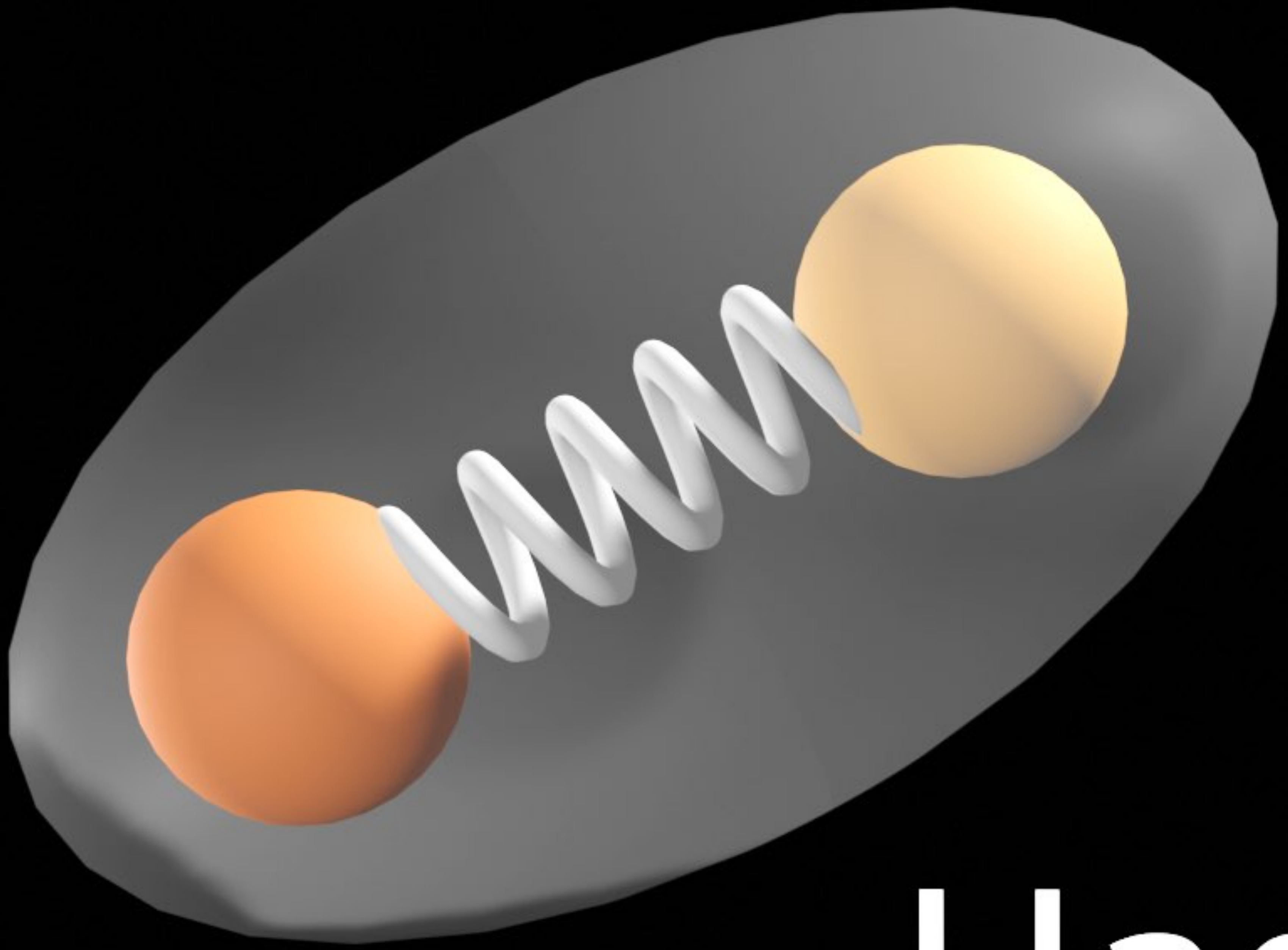
Υ(3S) R_{AA} / Υ(2S) R_{AA}



- Poor description of the new Υ(3S) data
  ➜ Excited state measurement is very useful
  - Constrain *feed down* contribution
  - Reduce systematics from *nPDF* in models

CMS-PAS-HIN-21-007

- X(3872)/ψ(2S) decreases wrt multiplicity in pp, but has hint of enhancement in pPb and PbPb
  - *What about pAu and AuAu?*

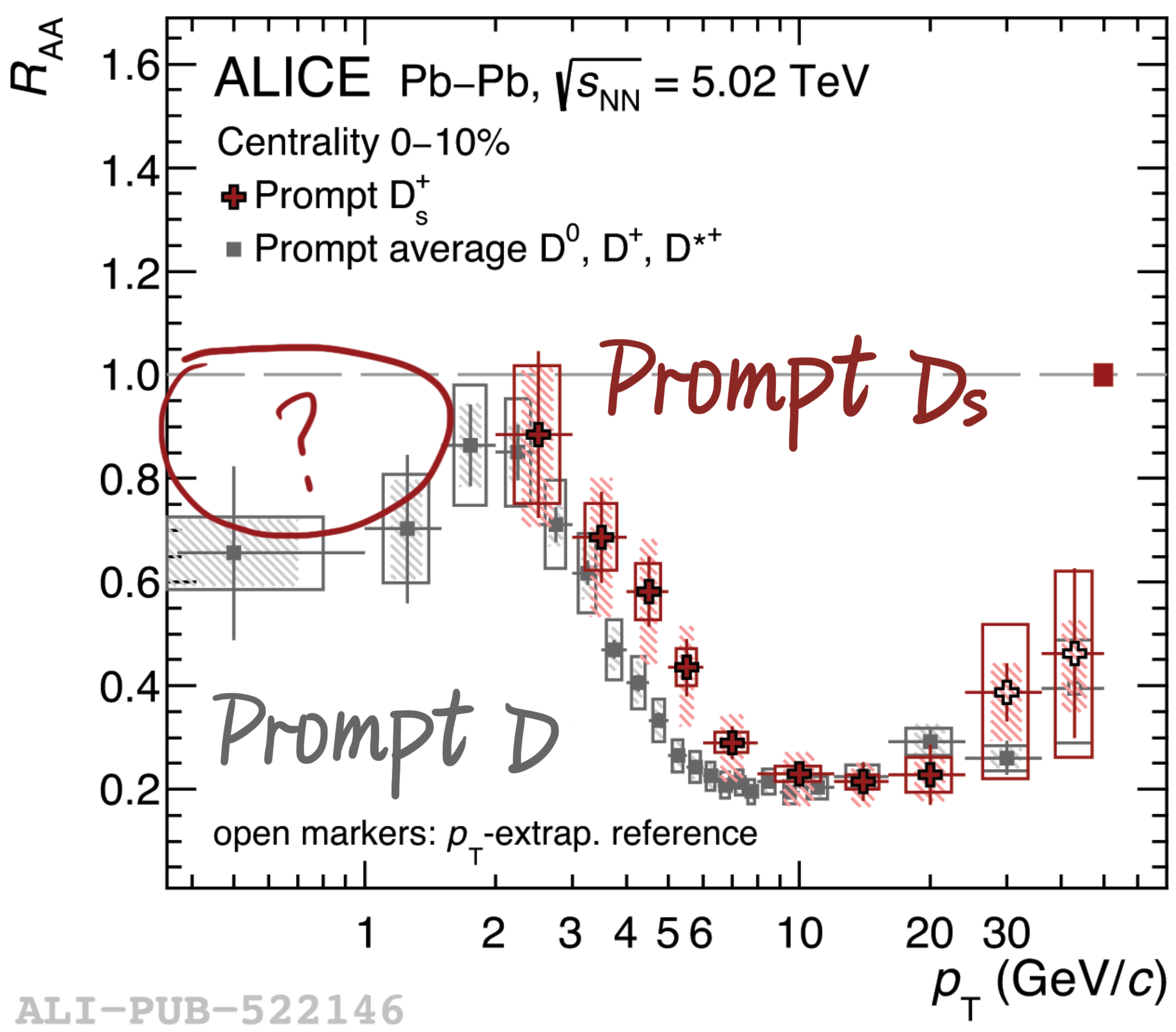


Hadronization

Click to see animation ↪

Strangeness Charm Mesons in PbPb

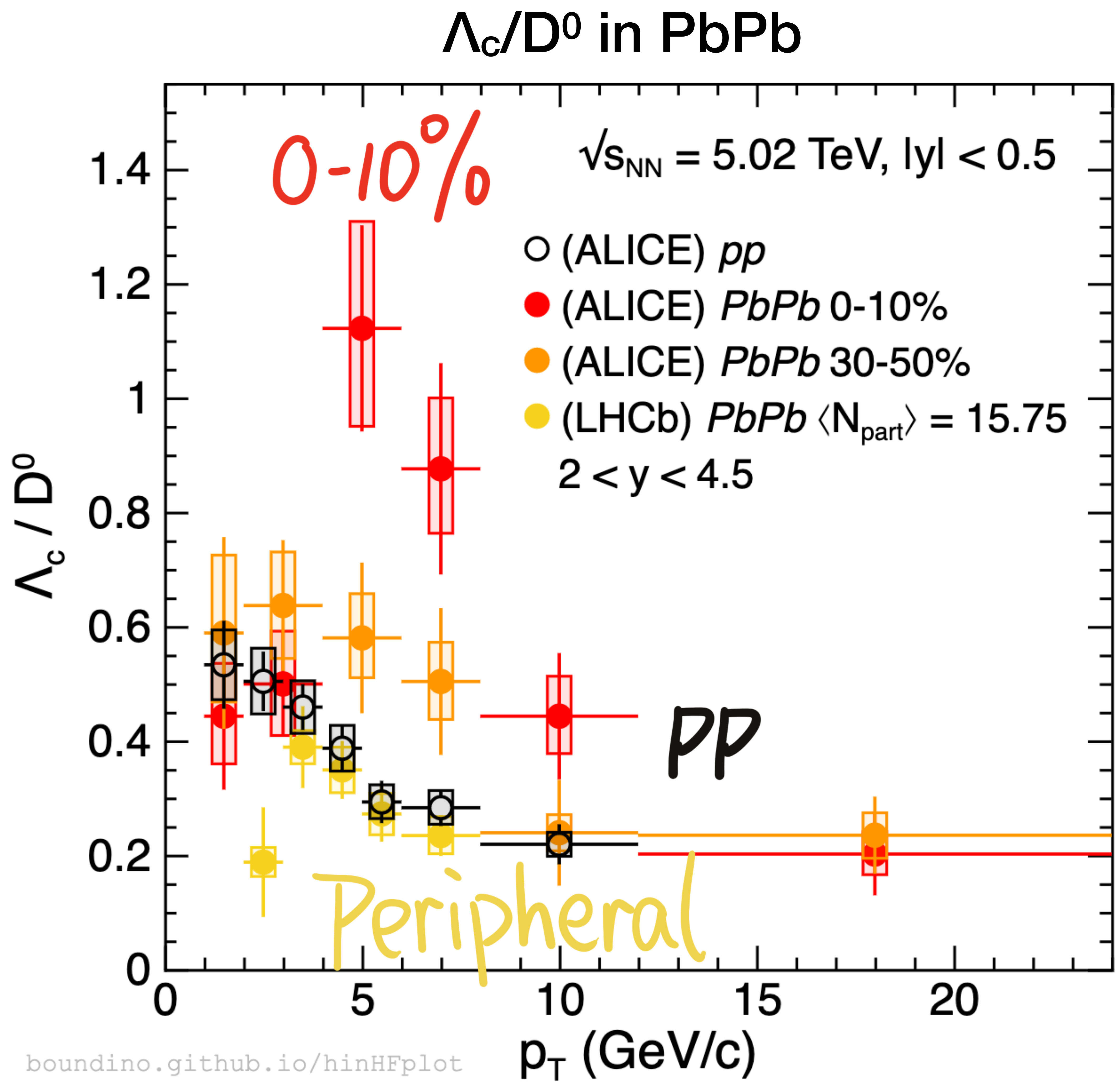
D_s R_{AA}



- Indication of enhanced production of D_s in PbPb collisions (2.3σ)
- *<u>What will happen at lower p_T?</u>*
  - Divergence of theoretical models

PLB 827 (2022) 136986

Heavy Flavor Baryons in PbPb



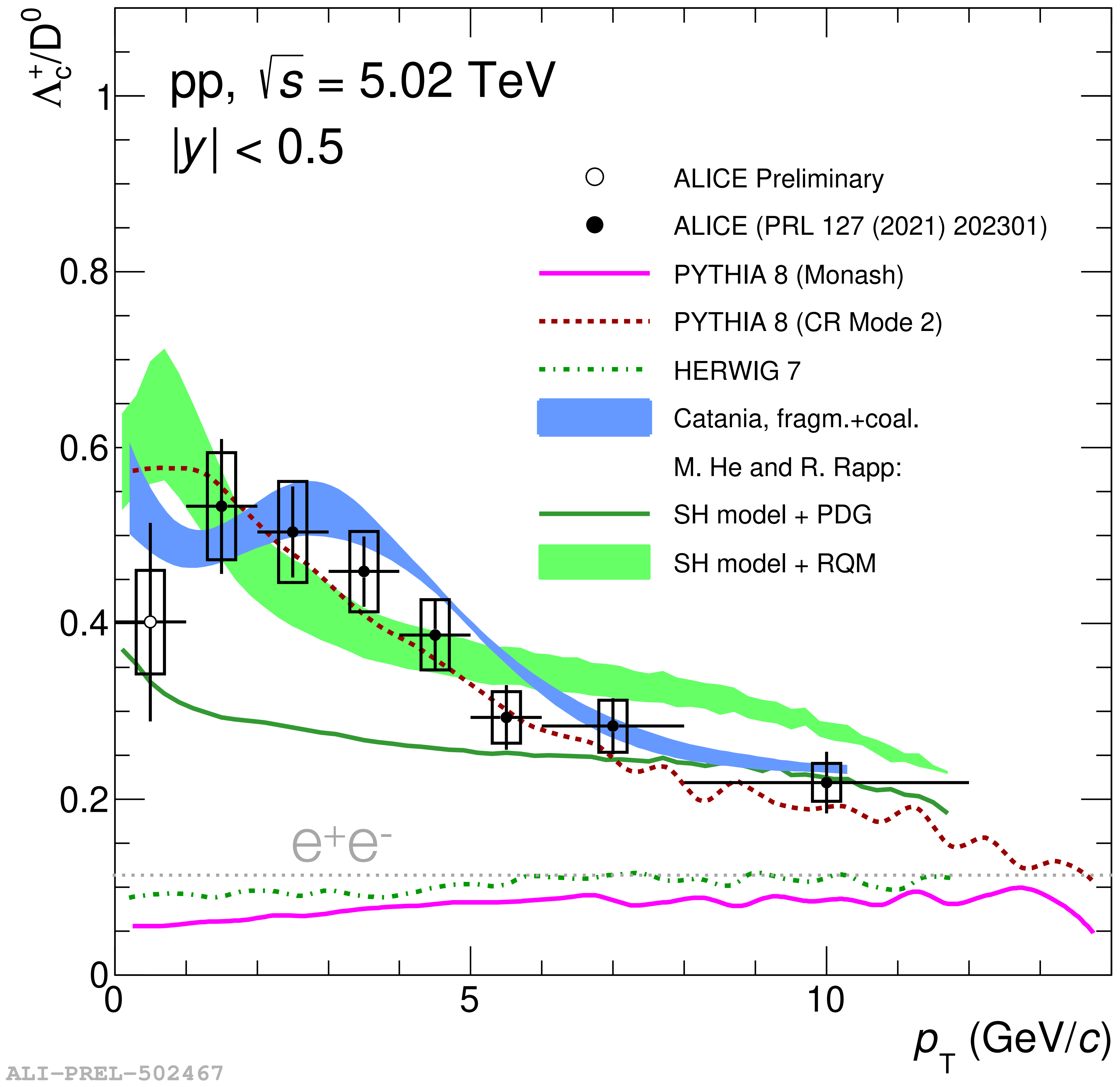
- Enhanced production of charmed baryons in PbPb
- Hint of lower ratio in very peripheral events than pp?
  - Note: different rapidity range ➜ *what's the role of rapidity dependence?*

arXiv:2112.08156

LHCB-PAPER-2021-046

Heavy Flavor Baryons in pp

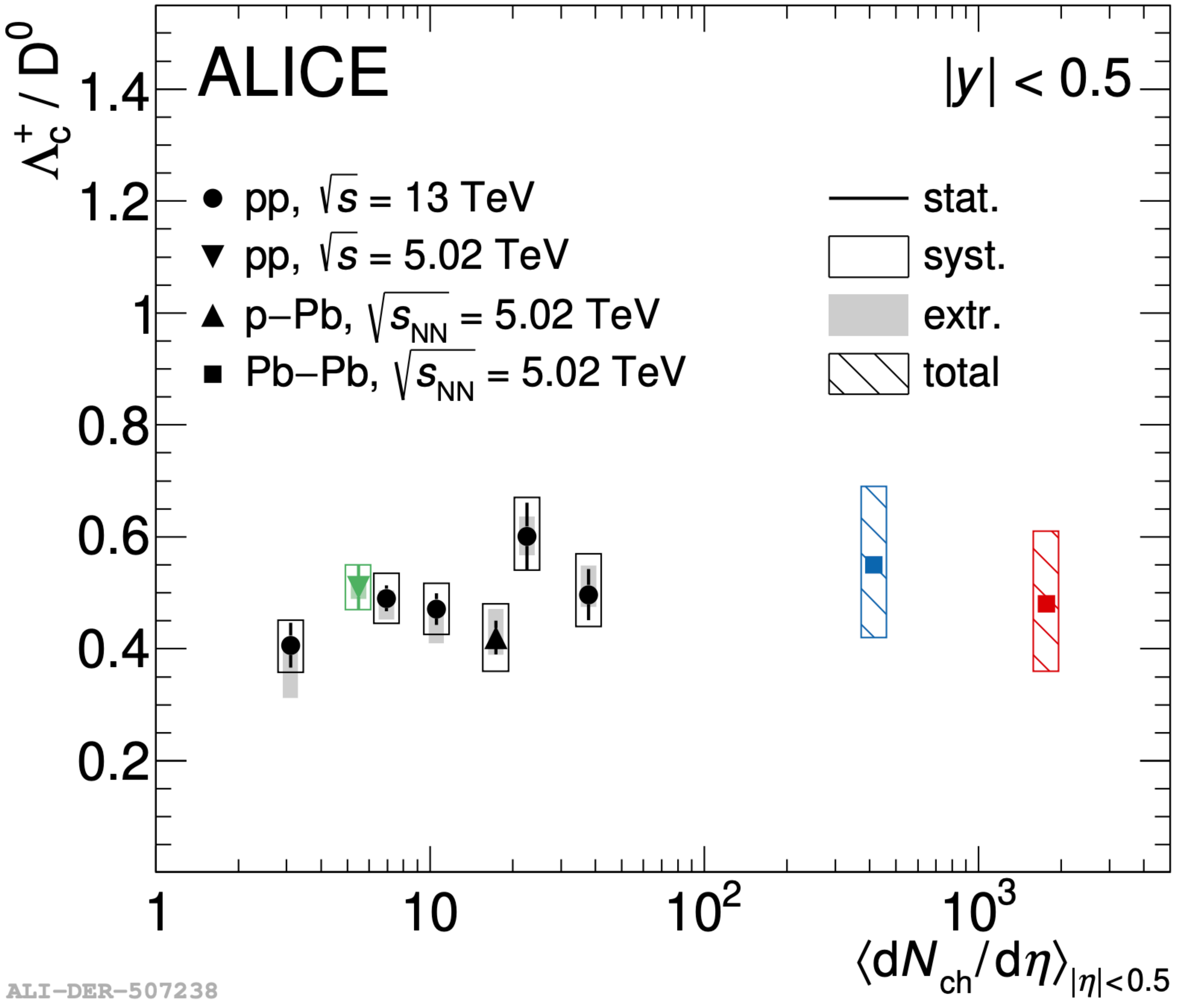
Λ_c/D^0 in pp



- Modification (wrt e^+e^-) already happens in pp
- Several efforts to describe the enhancement
  - Color reconnection
  - Coalescence + fragmentation
  - Additional excited baryons than PDG
- Then, the most low p_T bin is overestimated

Λ_c over Collision Systems

p_T-integrated Λ_c/D^0



- p_T integrated ratio is independent of collision system, multiplicity and energy
  - Redistribution instead of enhancement
- But indeed larger than e^+e^-
  - *What is the essential difference between e^+e^- and pp/pPb/PbPb?*

- Look forward to a full collision system and energy scan in LHC and RHIC

arXiv:2207.07590

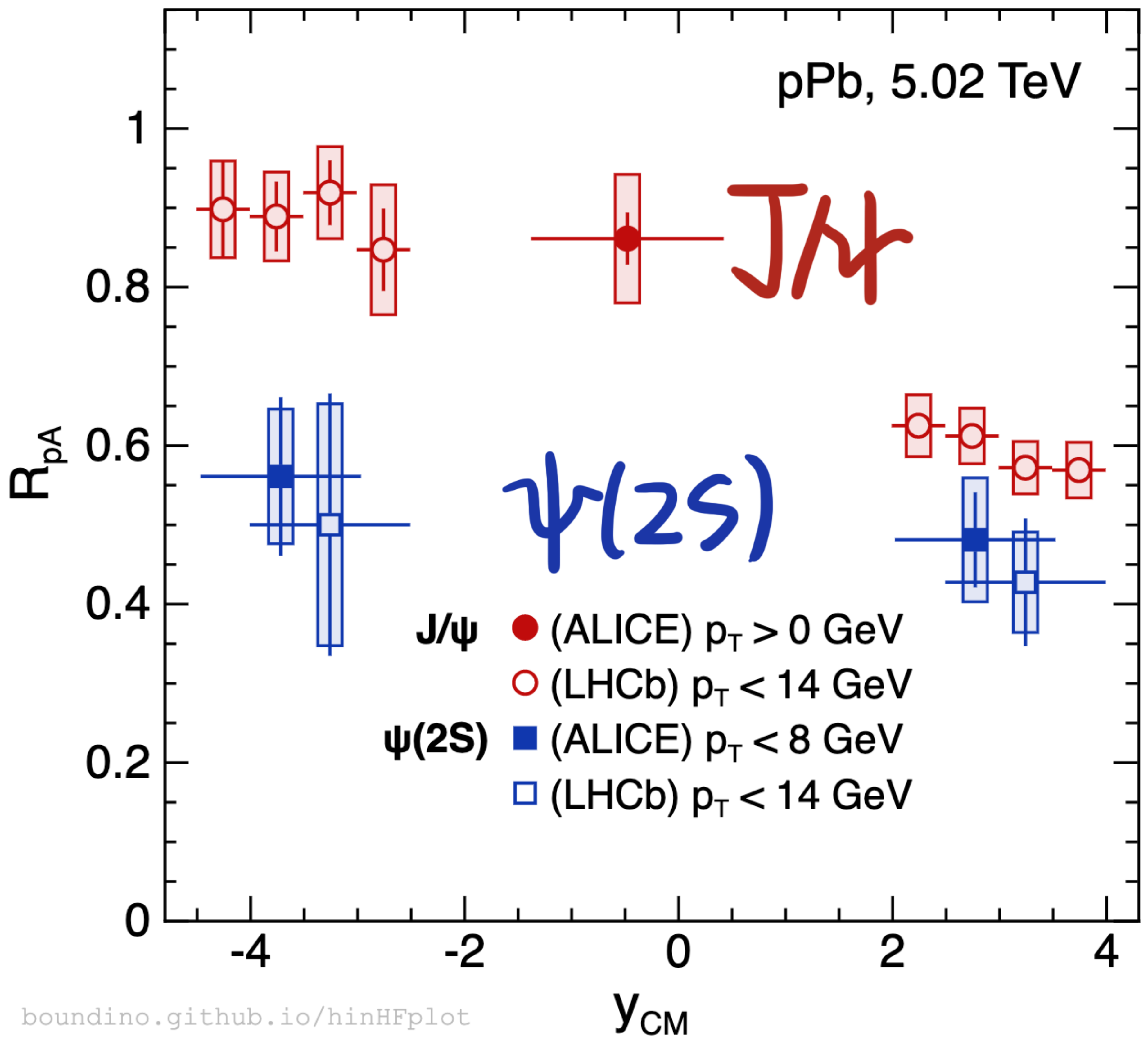
Section IV

Small Systems

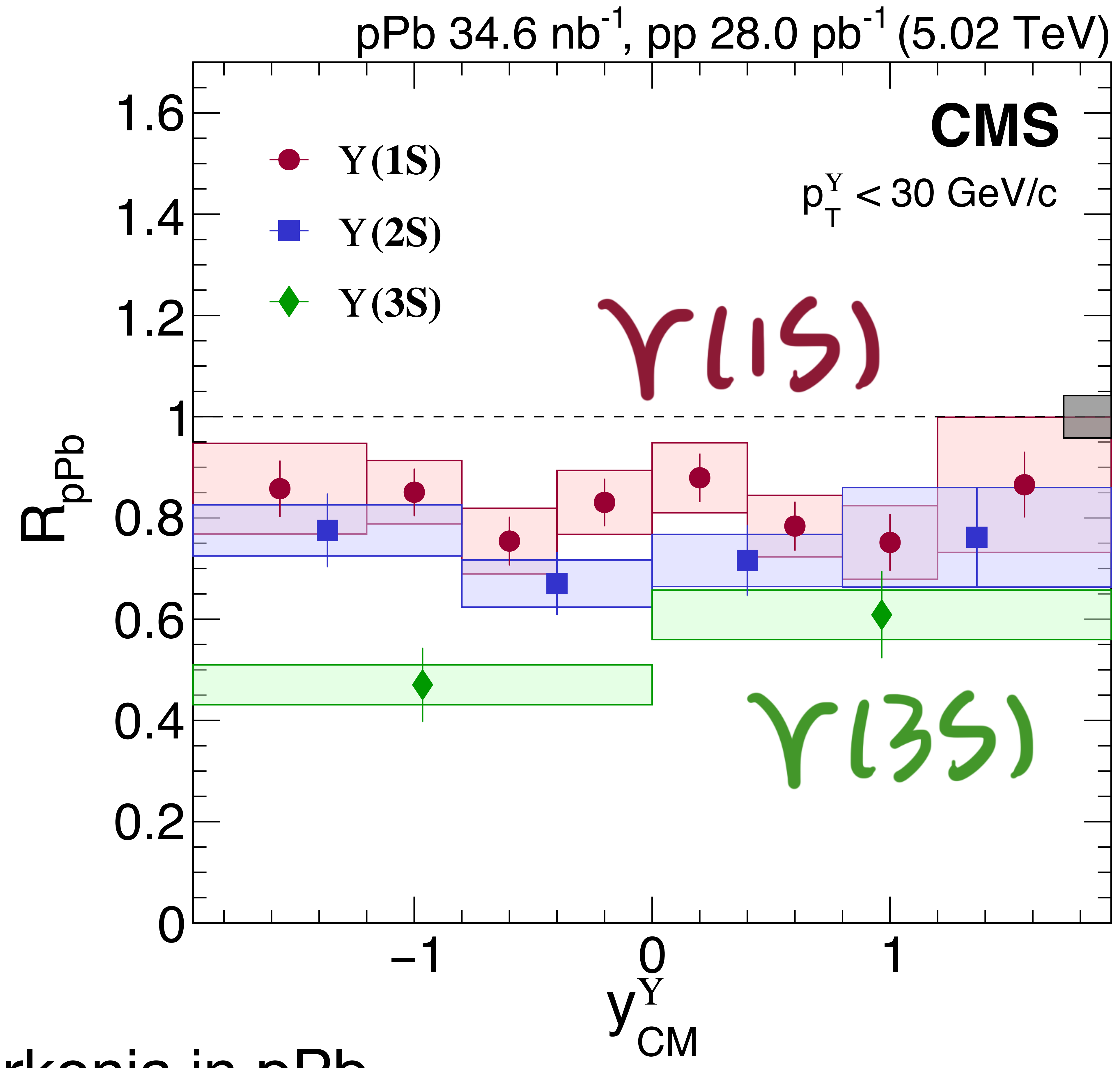
Medium or no medium?

Suppression of Quarkonia in pPb

ψ(nS) R_{pA}



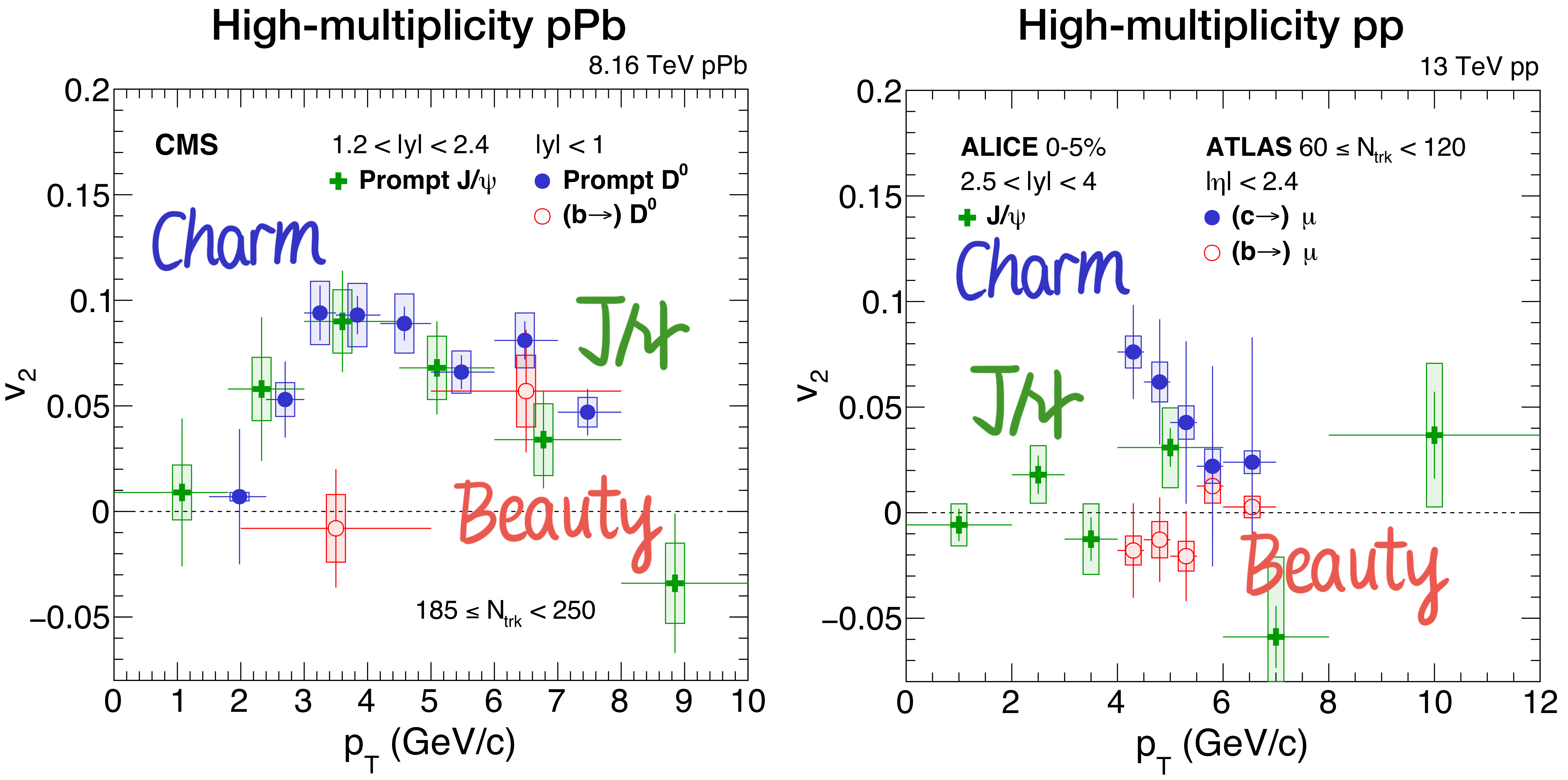
Υ(nS) R_{pA}



arXiv:2202.11807

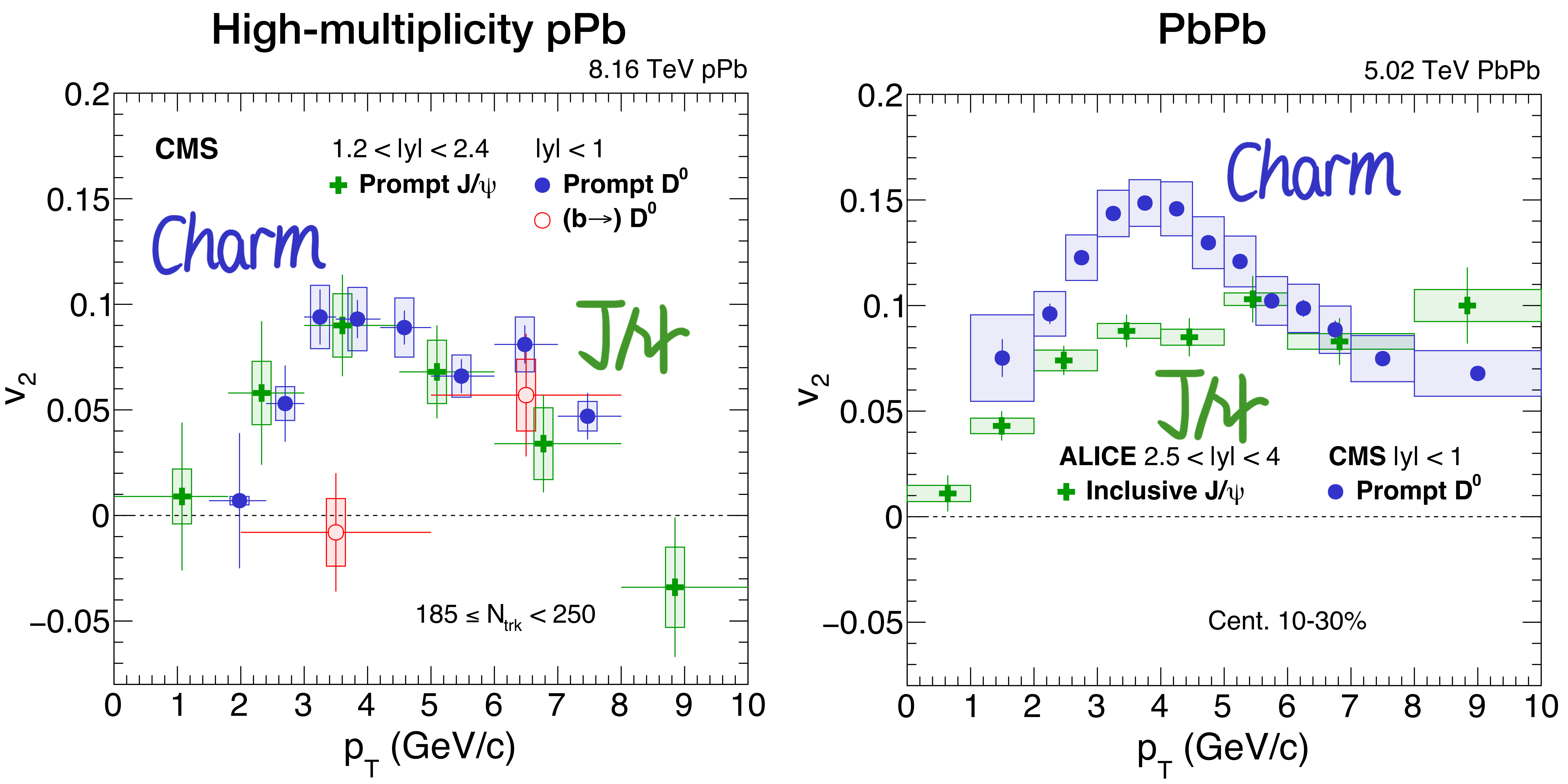
- Sequential suppression pattern of quarkonia in pPb
- Excited state modification beyond nPDF
- Studied with comover and medium interaction ➜ *How do we distinguish them?*

Heavy Flavor Flow in Small Systems



- Open charm flow signal observed in both pp and pPb
- Non-zero J/ψ v_2 in pPb but not in pp

Heavy Flavor Flow in Small Systems



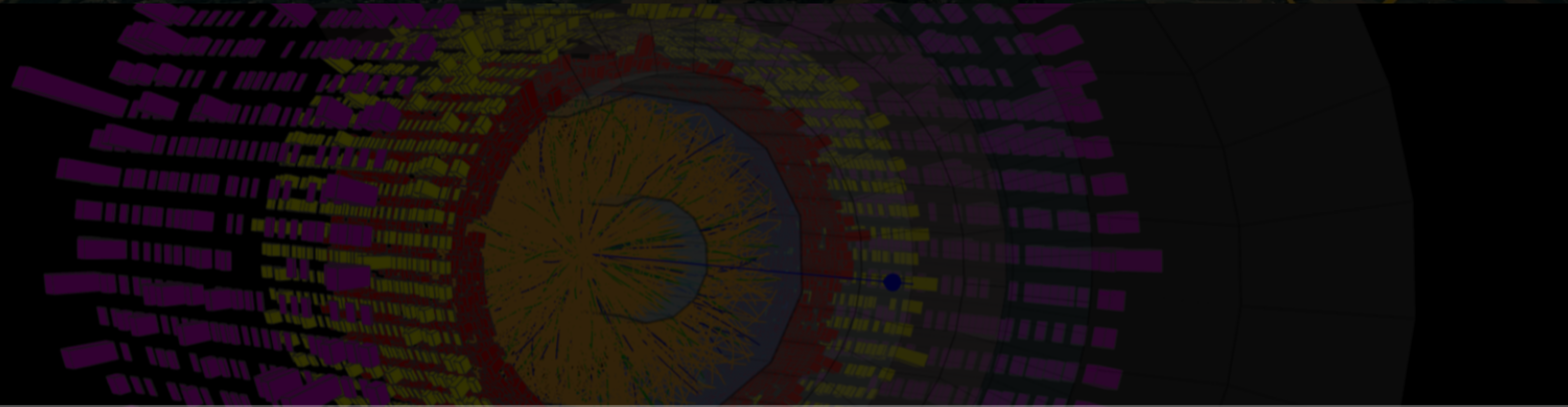
- Different flavor dependence of v_2 in pPb and PbPb ➜ hint of different source?
- How do we *distinguish initial and final state effects*?

Impressions on Small Systems

- Many medium-like effects (charm flow, sequential quarkonia suppression and modification of hadronization) are observed in small collision systems
- There should be some final state effects, but no sign of jet quenching signal
- We don't know how to isolate initial and final state effects
- We don't fully understand the role of high multiplicity, and need a more coherent definition of event classes across systems and experiments

Summary

Look forward to the answers from sPHEavyNIX!



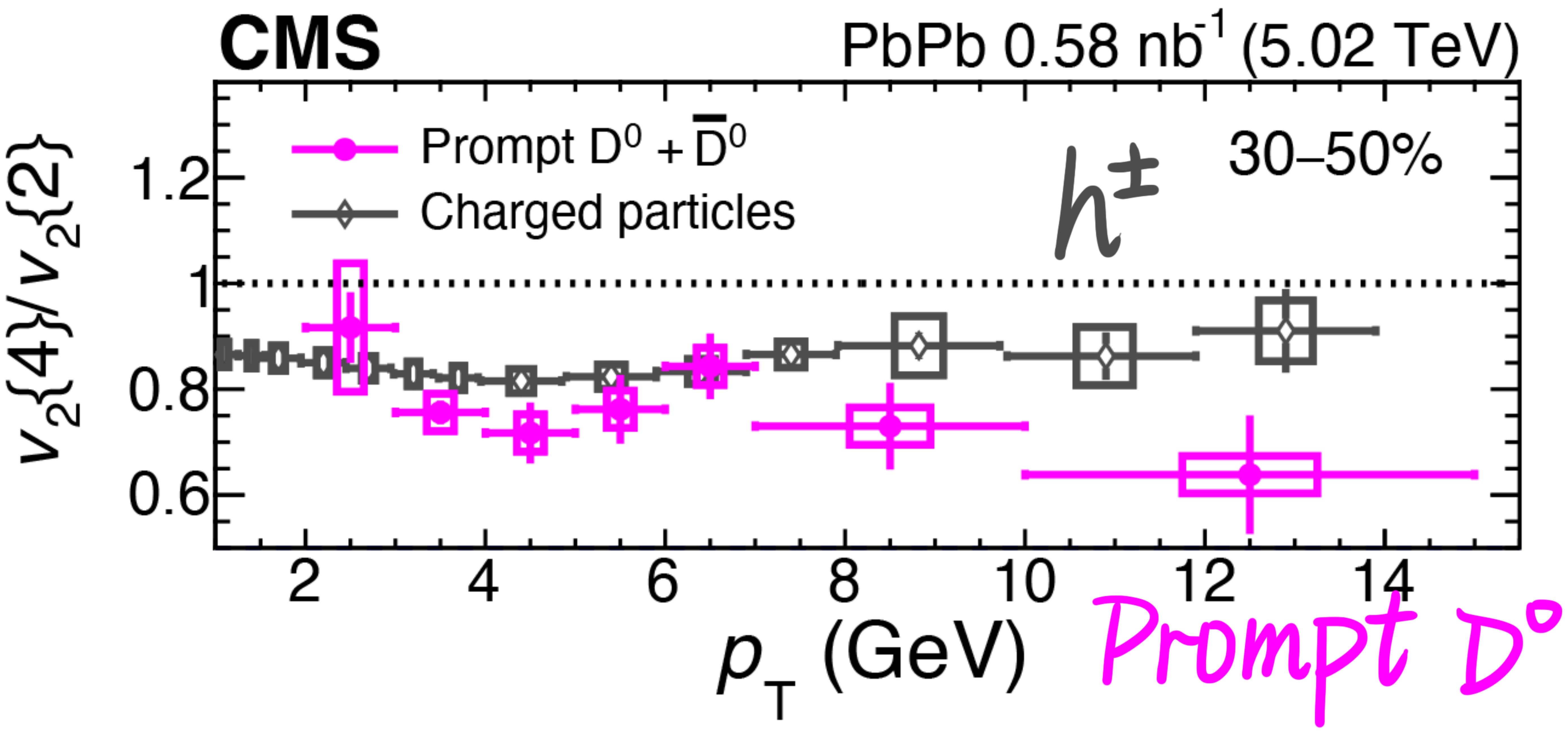

Isabelle
Thanks for your attention!

Back up

Thanks for your attention!

Probe Initial Fluctuations: D^0 $v_2\{4\}$

Prompt D^0 $v_2\{2\}/v_2\{4\}$



- Fluctuations of both initial geometry (soft) and energy loss (hard)
  - can be distinguished by:
- Prompt D^0 $v_2\{4\}/v_2\{2\}$
  - Weak p_T dependence

    ➜ Initial geometry is the main source of fluctuations

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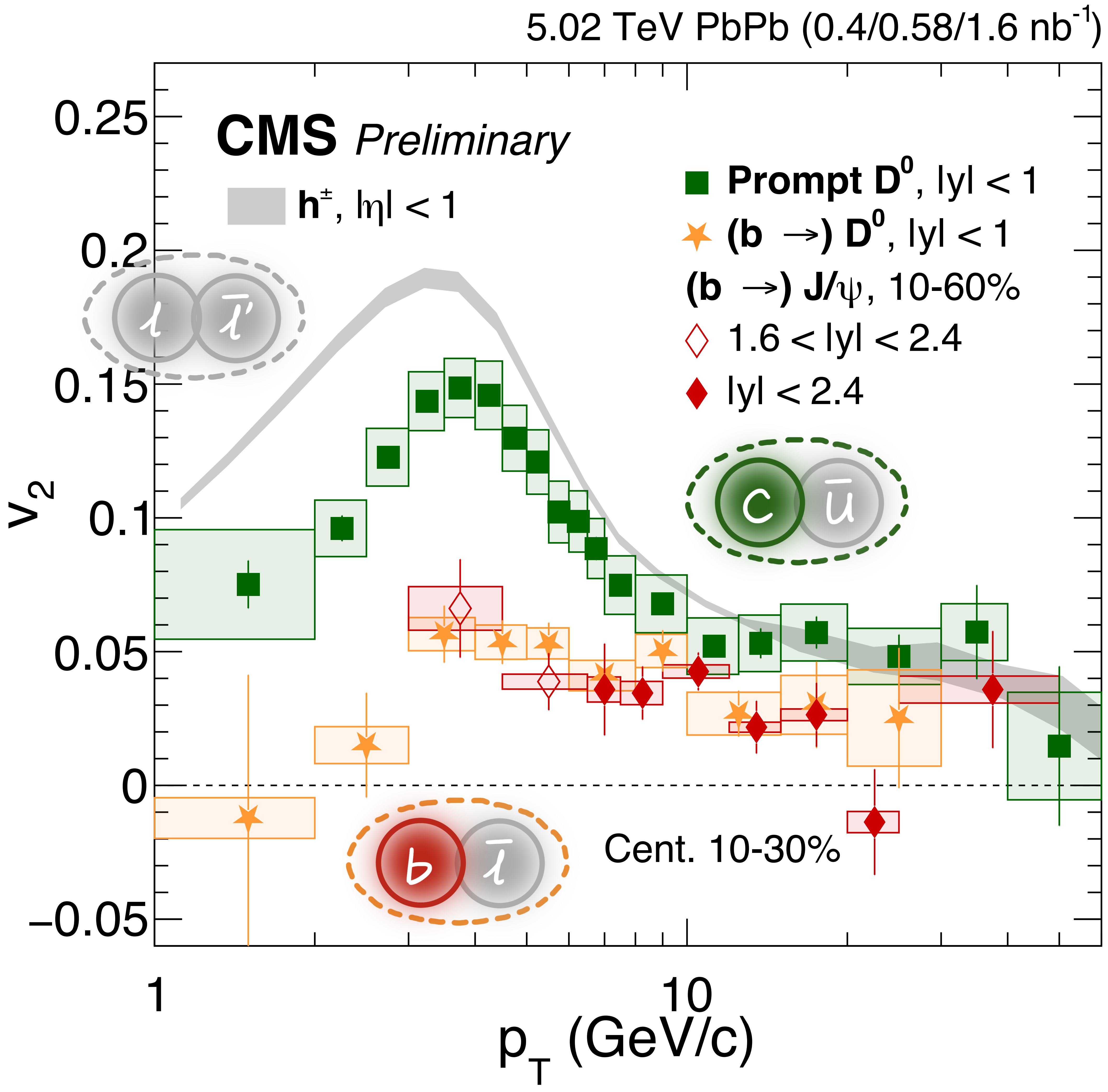
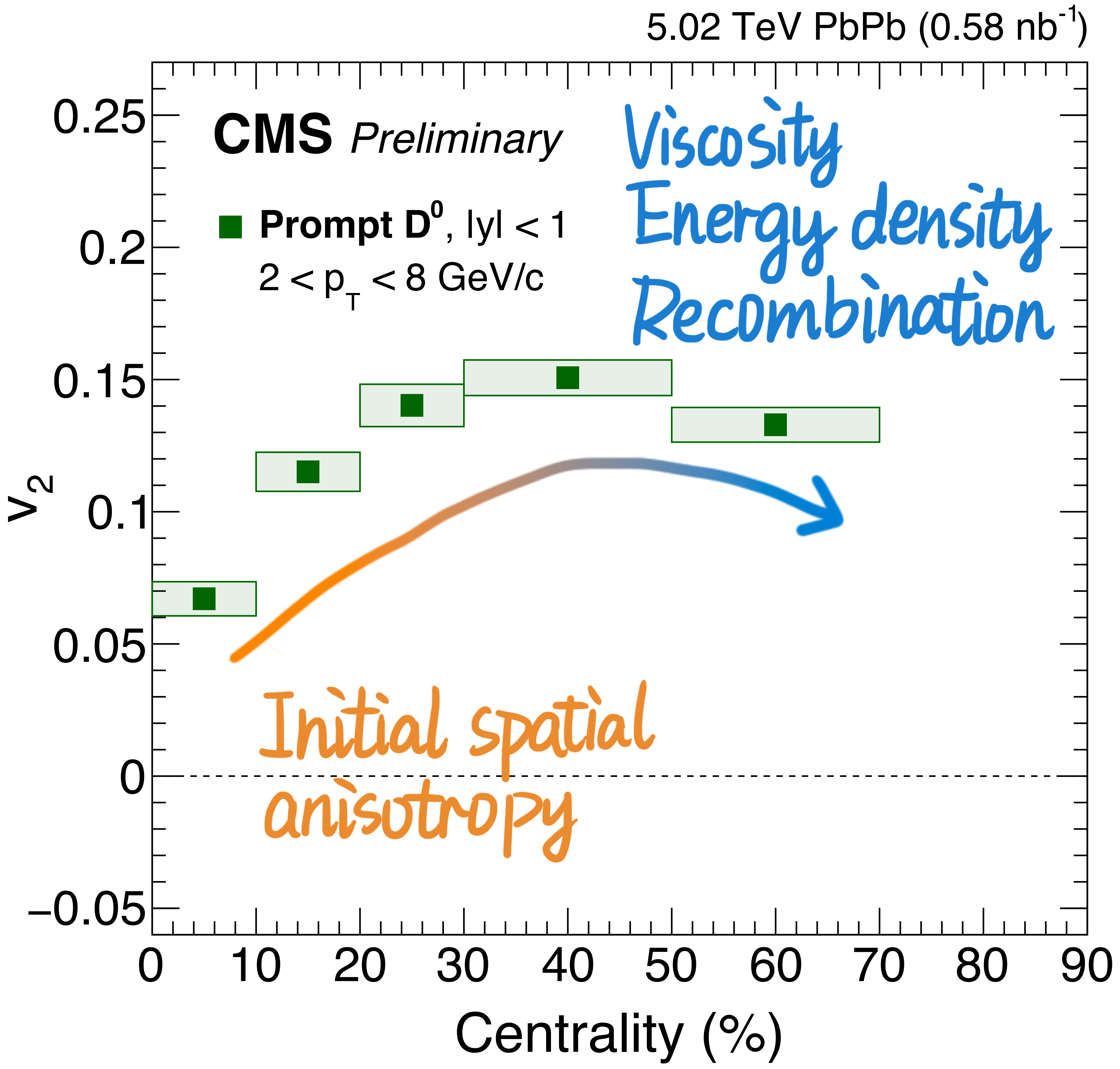
Open Beauty v_2: Full Flavor Picture



- Unique beauty flow info covering wide kinematic range
  - (b→) D^0 v_2 consistent with (b→) J/ψ v_2
- Low p_T: Similar peak structure as other flavors
  - Open beauty v_2 < Open charm v_2 < Light v_2
  - ➜ Weaker collectivity of heavy than light quark
  - ➜ Recombination
- High p_T: All flavors tend to converge
  - Mass effect disappears

PLB 816 (2021) 136253
PLB 776 (2017) 195
CMS-PAS-HIN-21-003
CMS-PAS-HIN-21-008

HF v_2: Centrality Dependence



- v_2 increase and then decrease from central to peripheral events
  ➜ as expected by hydrodynamics
  ➜ but different effects work differently for different flavors

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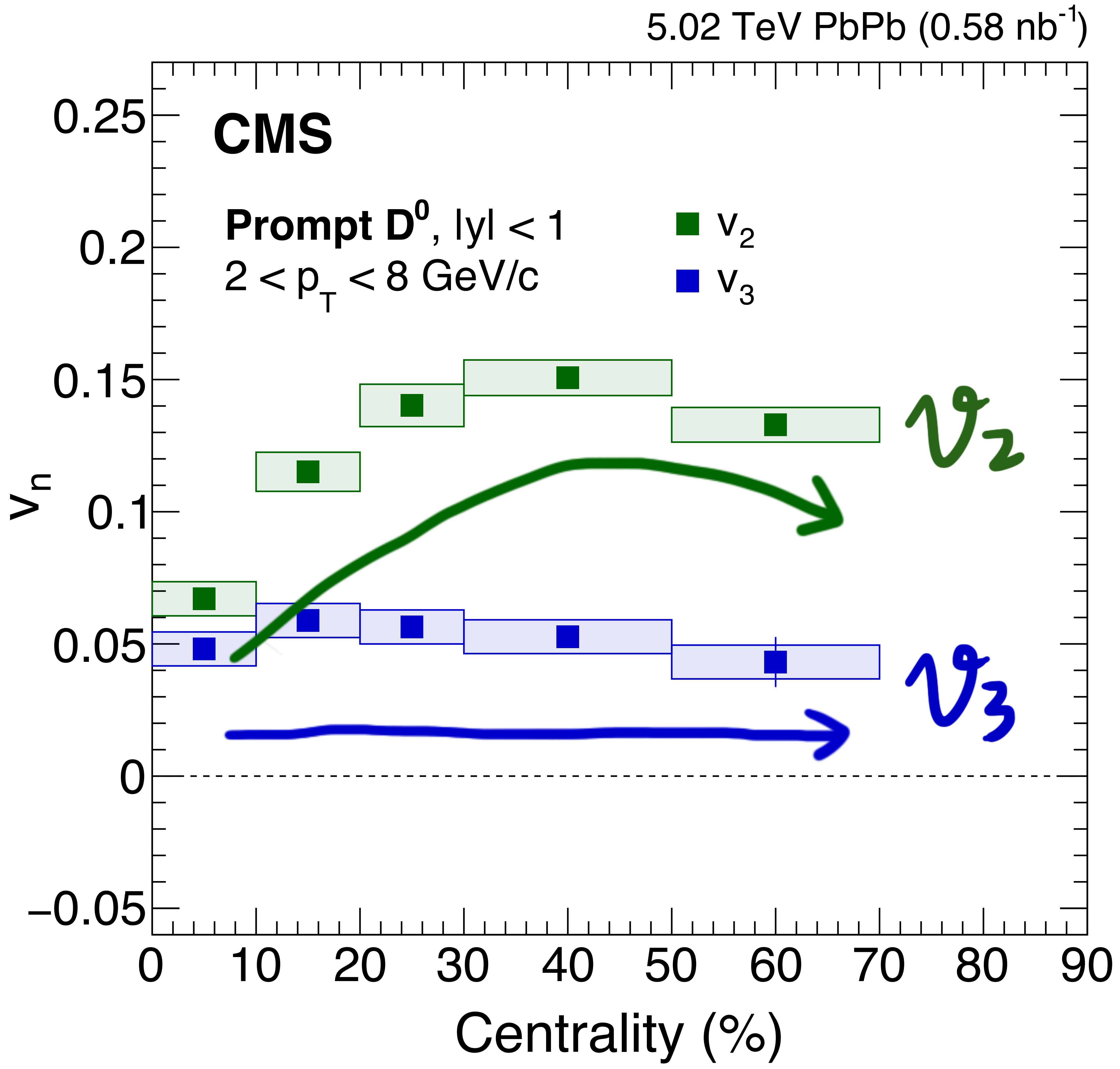
HF v_n: Centrality Dependence



- Centrality dependence is strong for v_2 and weak for v_3
  ➜ expected by hydrodynamics

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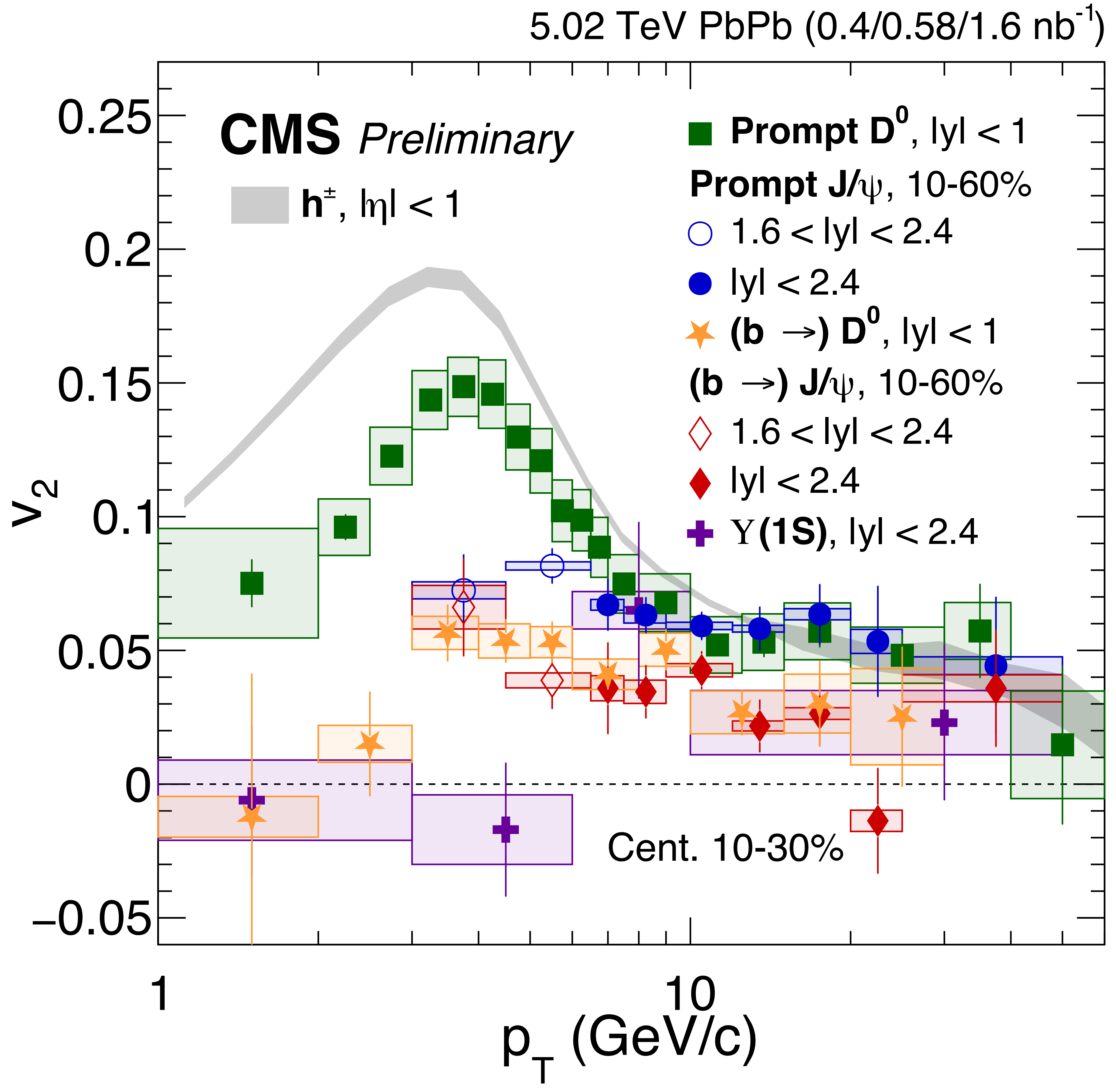
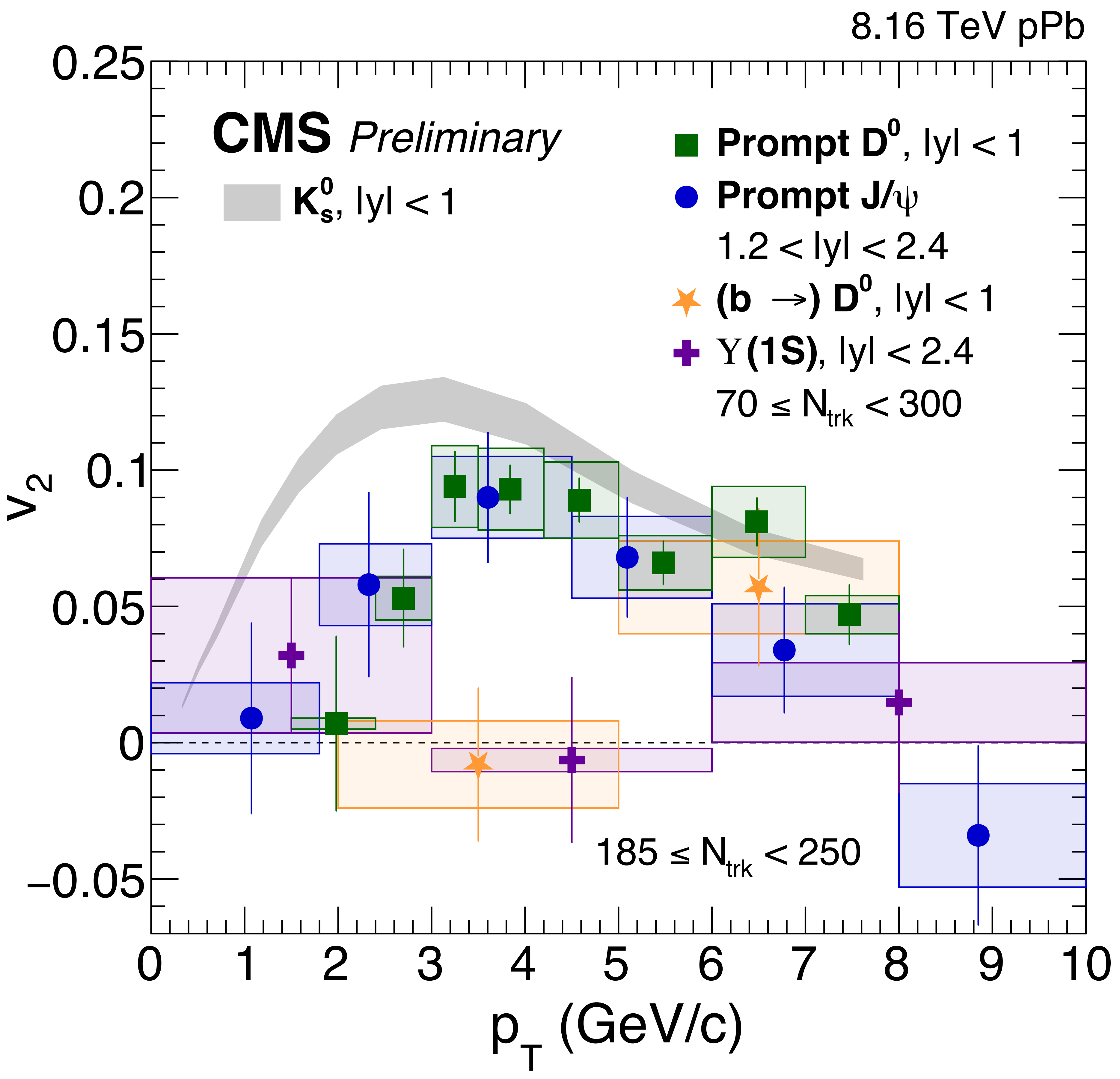
Summary: CMS Heavy Flavor v_2 Zoo

PbPb @ 5.02 TeV



pPb @ 8.16 TeV



$h^{\pm}$

D^0

J/ψ

$b \to D^0$

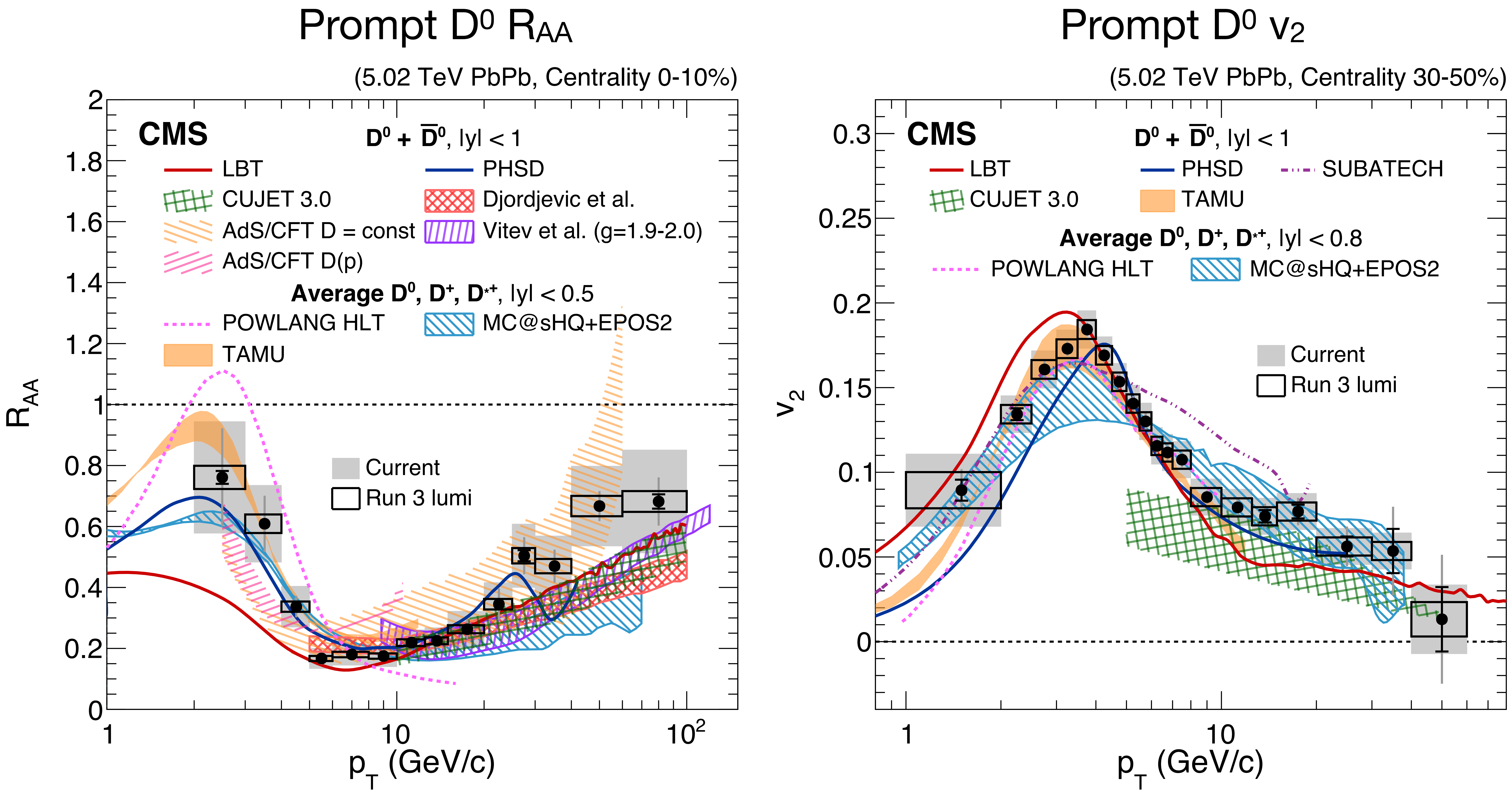
$b \to J/\psi$

$\Upsilon(1S)$

Reference

- Abundant physics behind these high precision and unique measurements from CMS!
- Challenging for models to reproduce data across all systems and flavors

Model Comparison: Open Charm (Run 3)

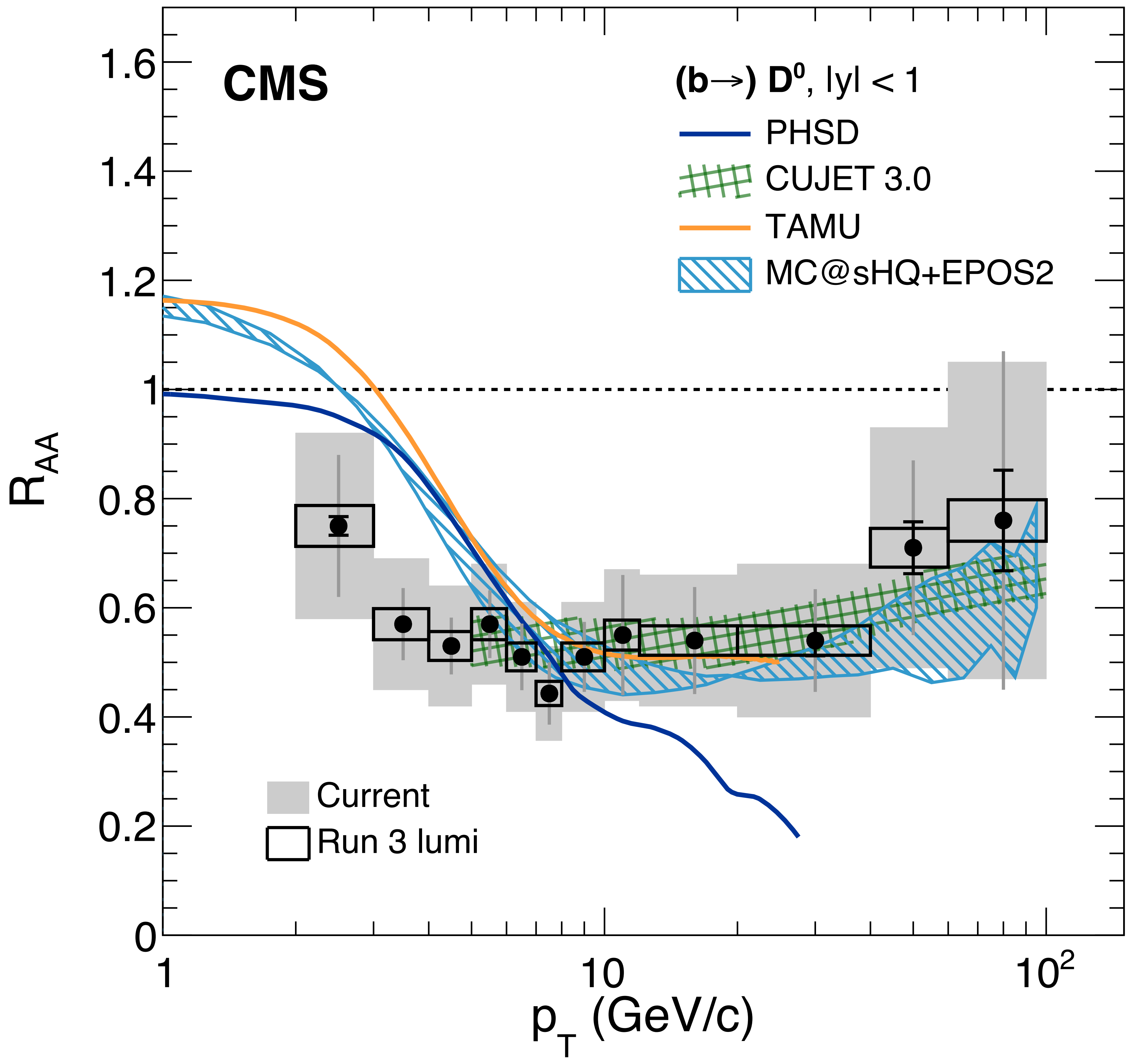


- Run 3 data has very strong discrimination power for models

Model Comparison: Open Beauty

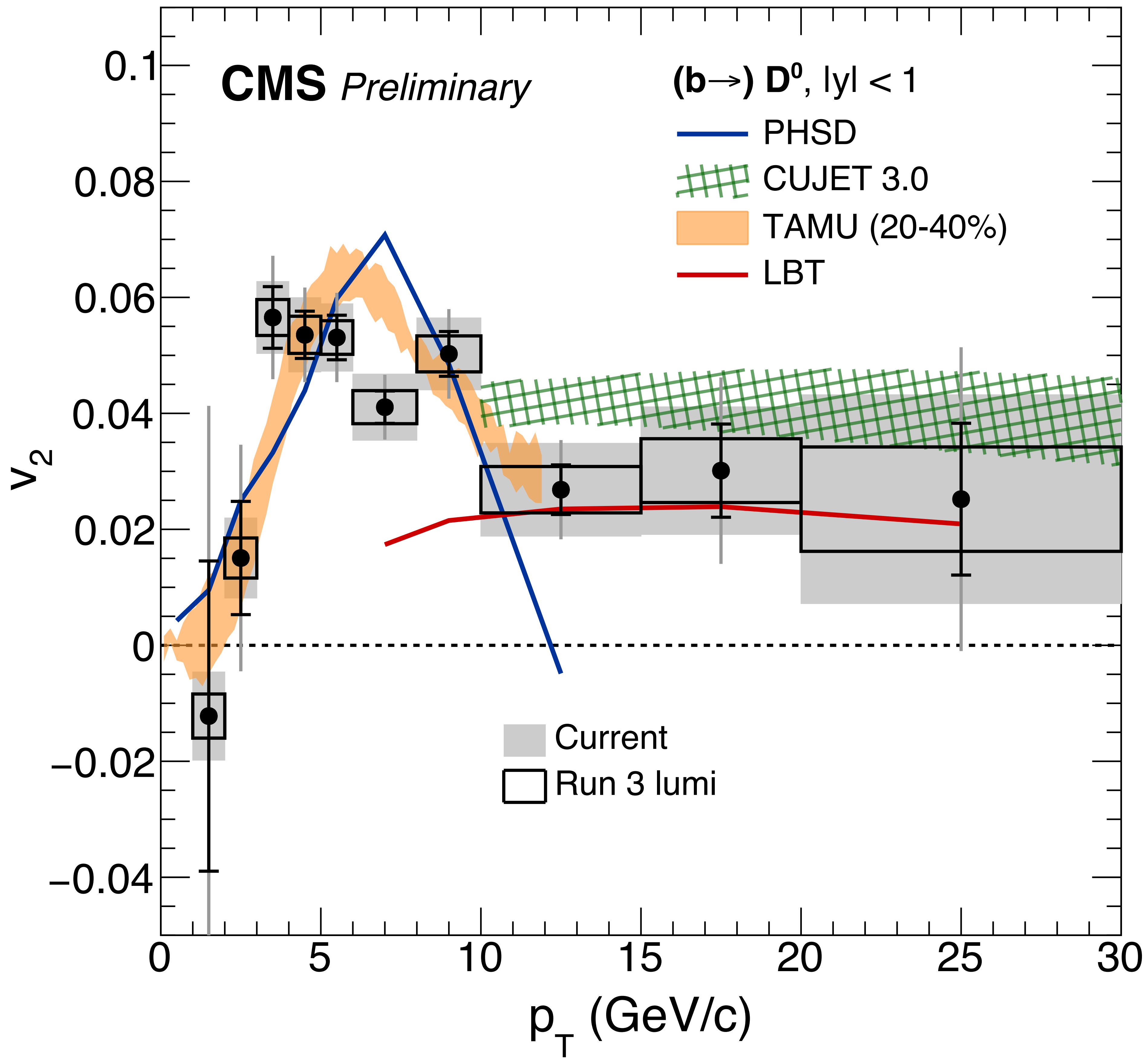
(b→) D^0 R_{AA}

(5.02 TeV PbPb, Centrality 0-100%)



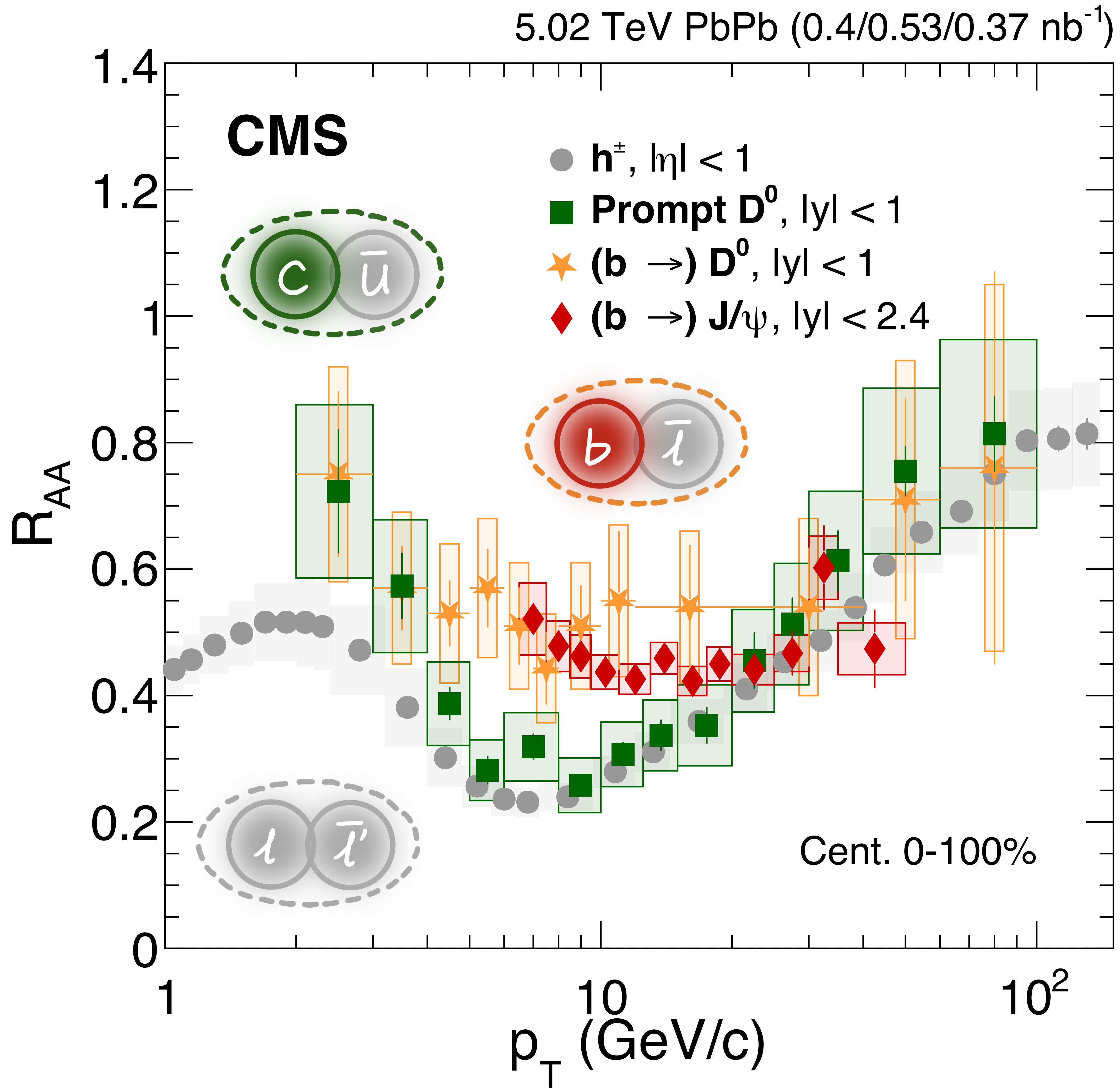
(b→) D^0 v_2

(5.02 TeV PbPb, Centrality 10-30%)



- Look forward to more calculations of open beauty

Beauty Energy Loss: Flavor Dependence

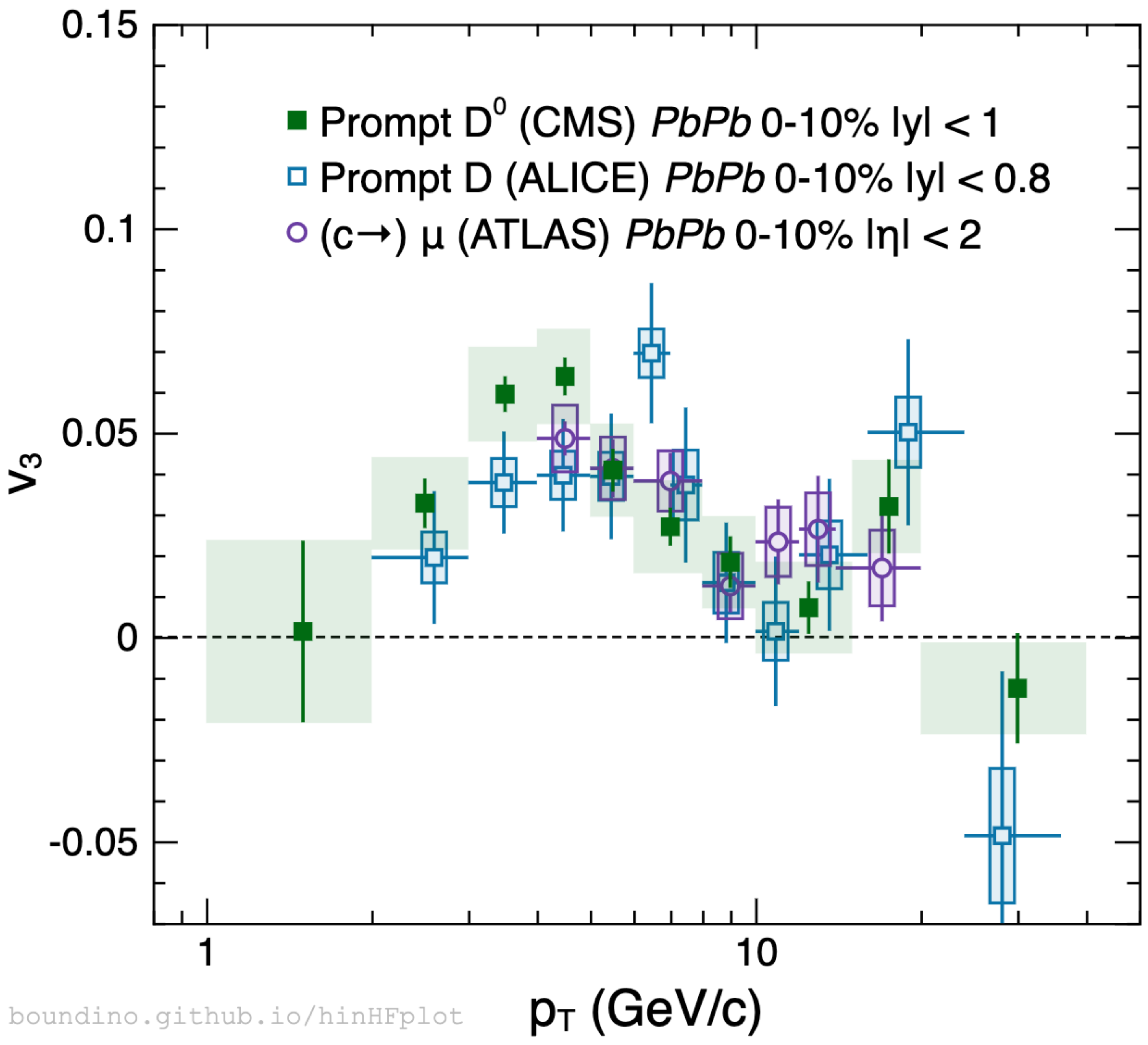


- Flavor difference at low and intermediate p_T
- Convolution of many effects
  - Mass dependent e-loss (dead cone effect)
  - Shadowing
  - Flow
  - Coalescence
  - p_T spectra, …

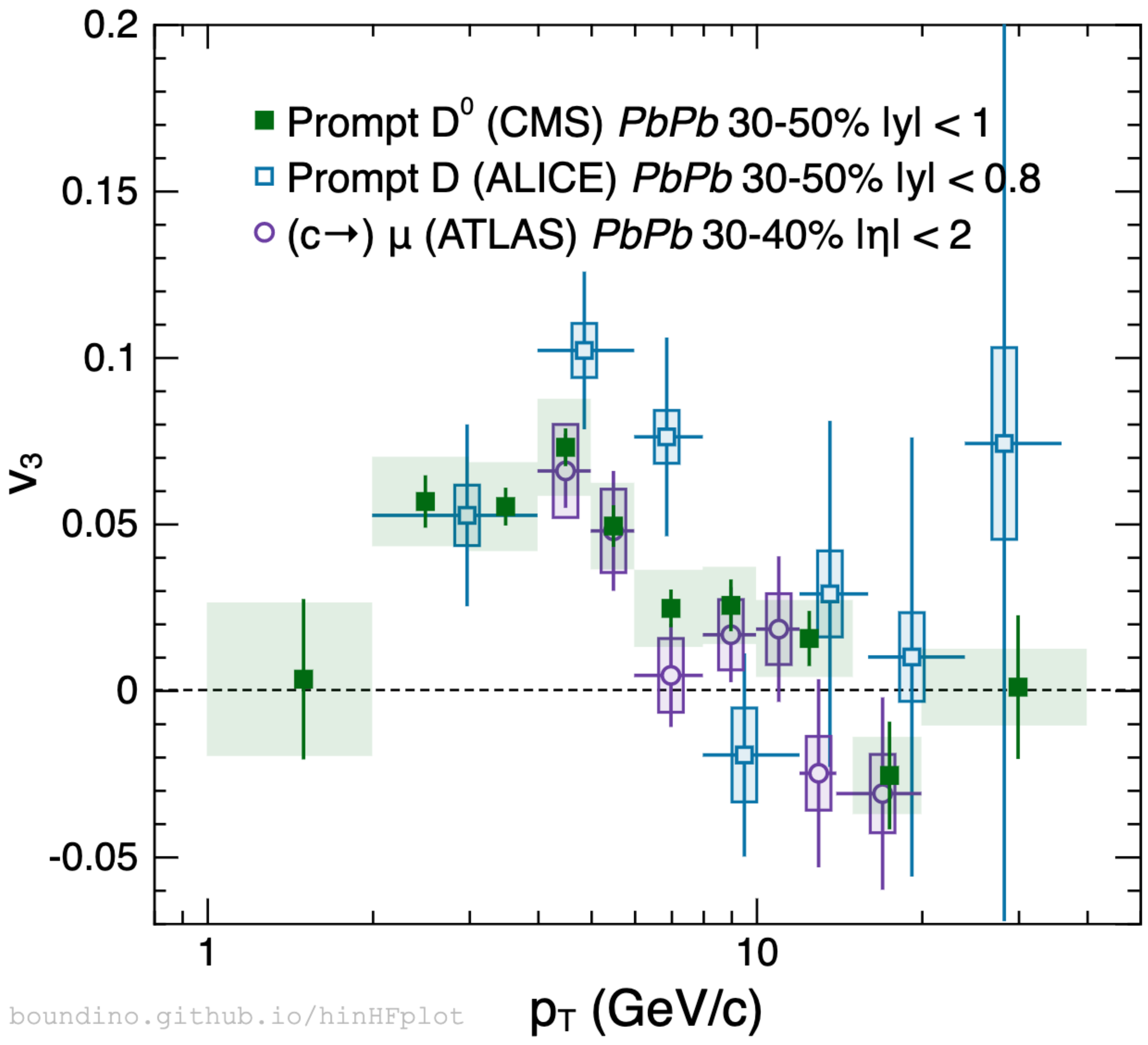
PLB 782 (2018) 474
PRL 123 (2019) 022001
EPJC 78 (2018) 509
JHEP 04 (2017) 039

Probe Initial State: Open Charm v_3

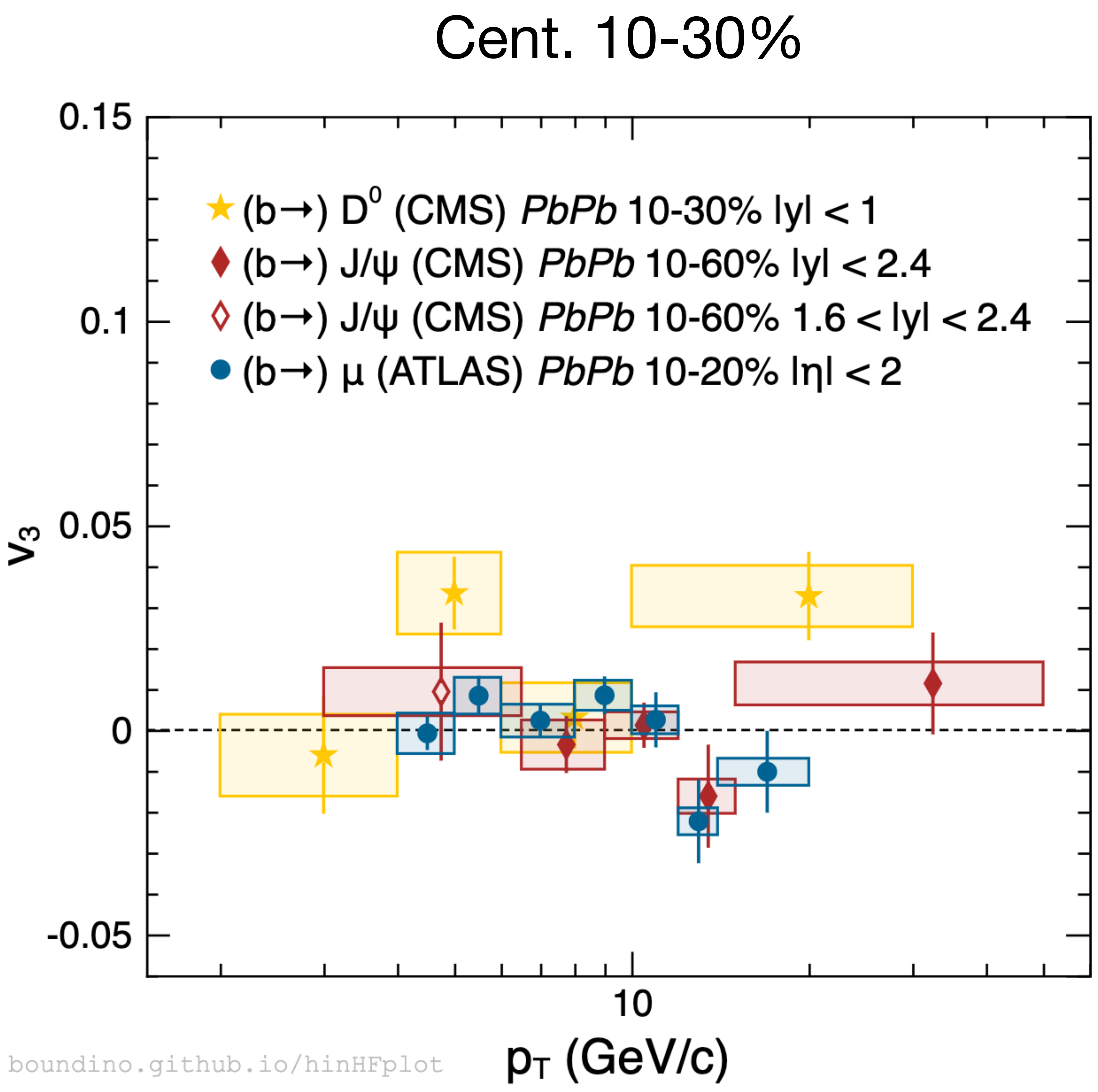
Open charm v_3 (0-10%)



Open charm v_3 (30-50%)

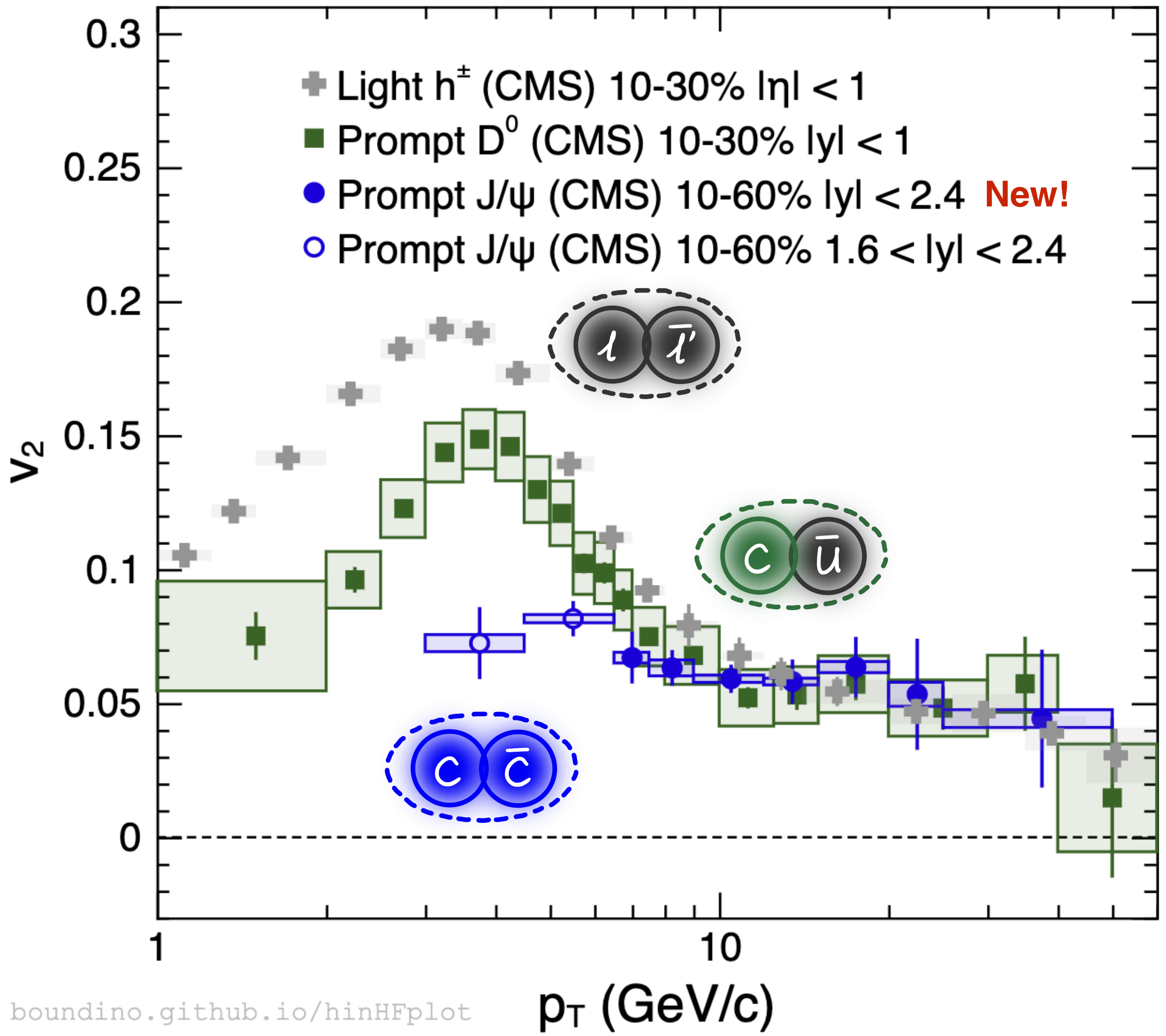


Probe Initial State: Open Beauty v_3



Charm v_2 in PbPb: Open vs. Hidden

v_2 vs. p_T



- High precision measurement over wide p_T range
- Low p_T: $v_2(h^{\pm})$ > v_2(Prompt D^0) > v_2(Prompt J/ψ)
  - ➡ Different constituent quarks
  - ➡ Recombination
- High p_T: $v_2(h^{\pm}) \approx v_2$(Prompt D^0) $\approx v_2$(Prompt J/ψ)
  - ➡ Mass effect disappears
  - ➡ Path-length dependence of energy loss
  - ➡ Non-zero v_2 up to high p_T = 50 GeV

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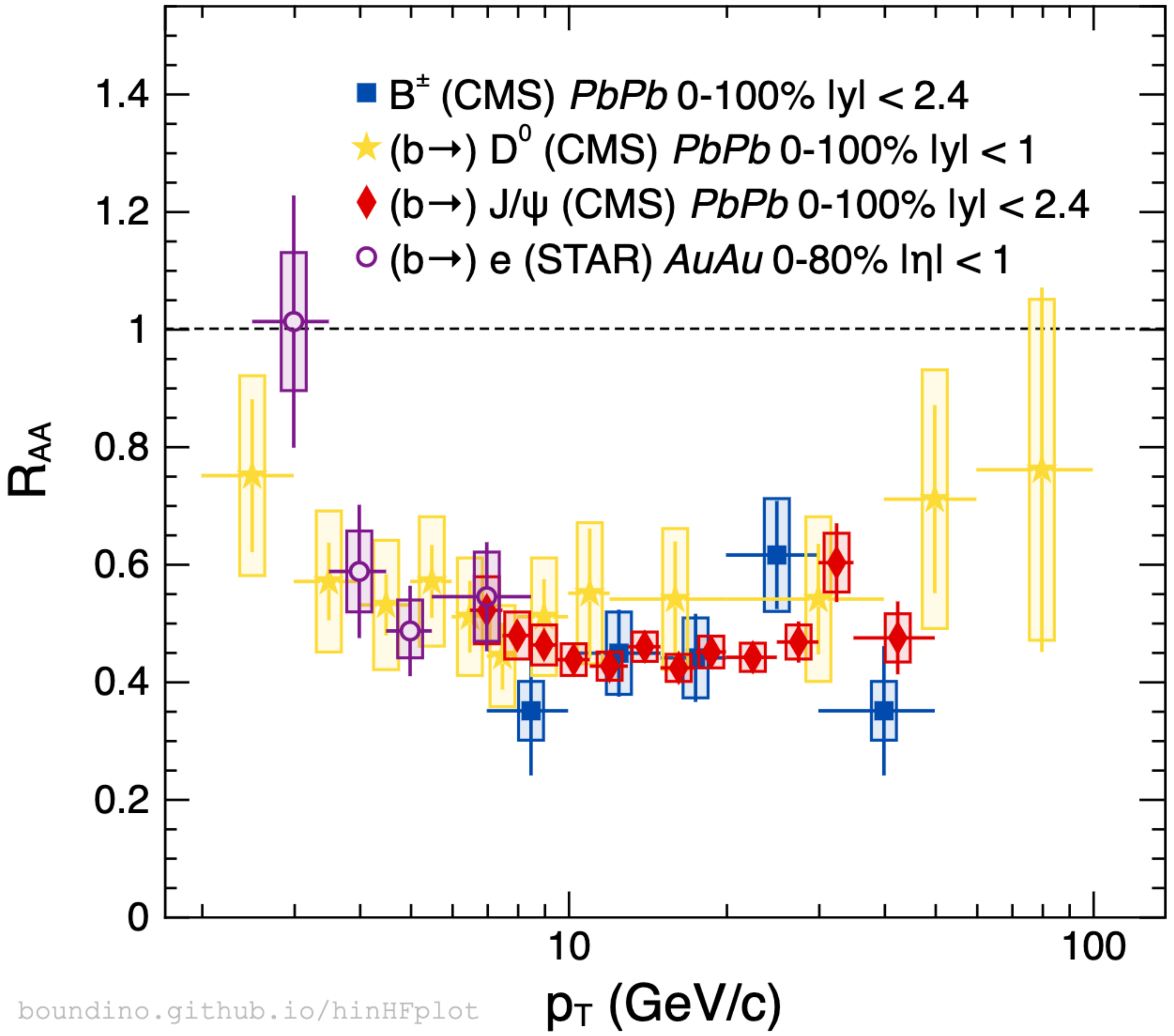
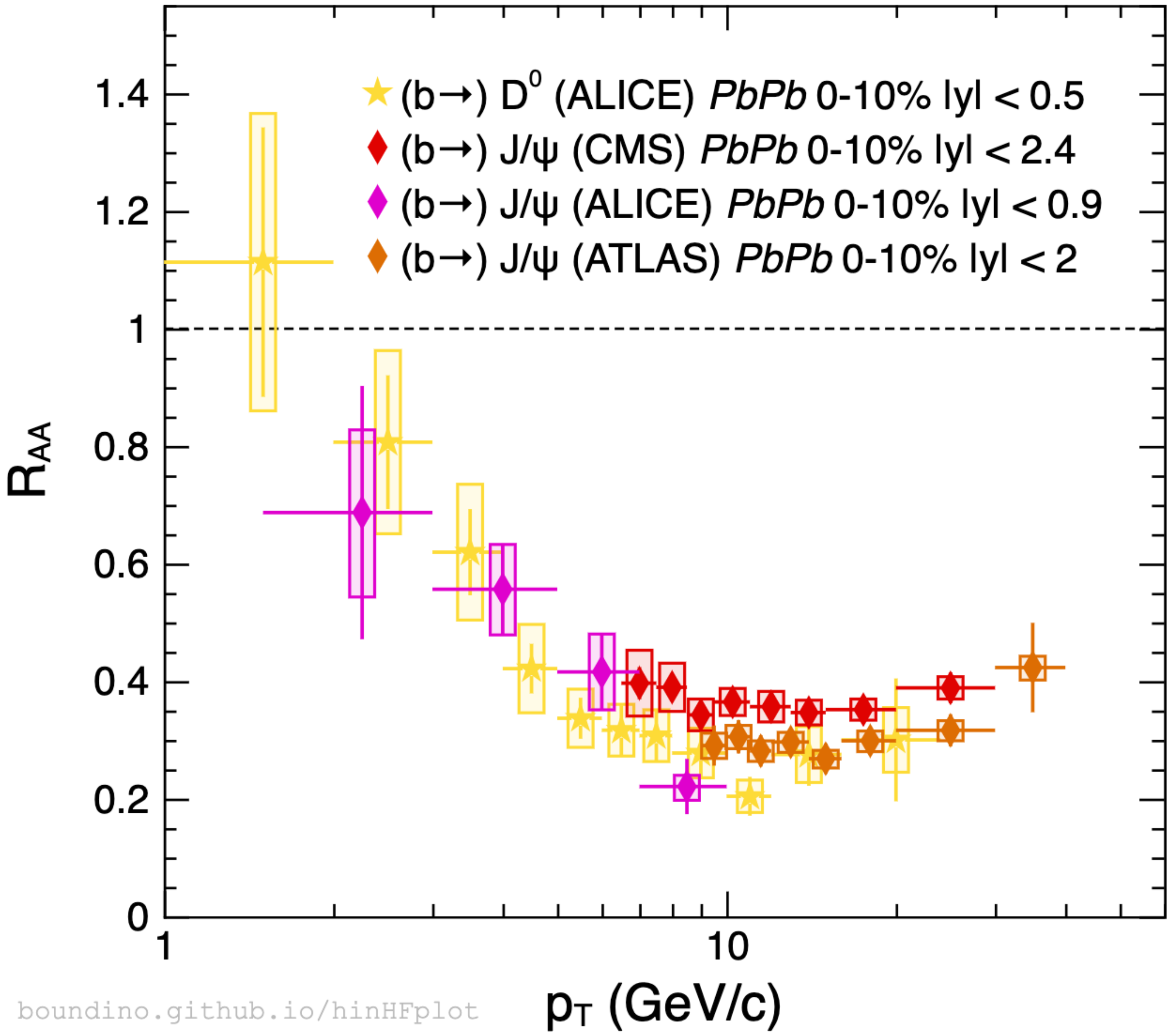
Open Beauty v_2: Across Experiments

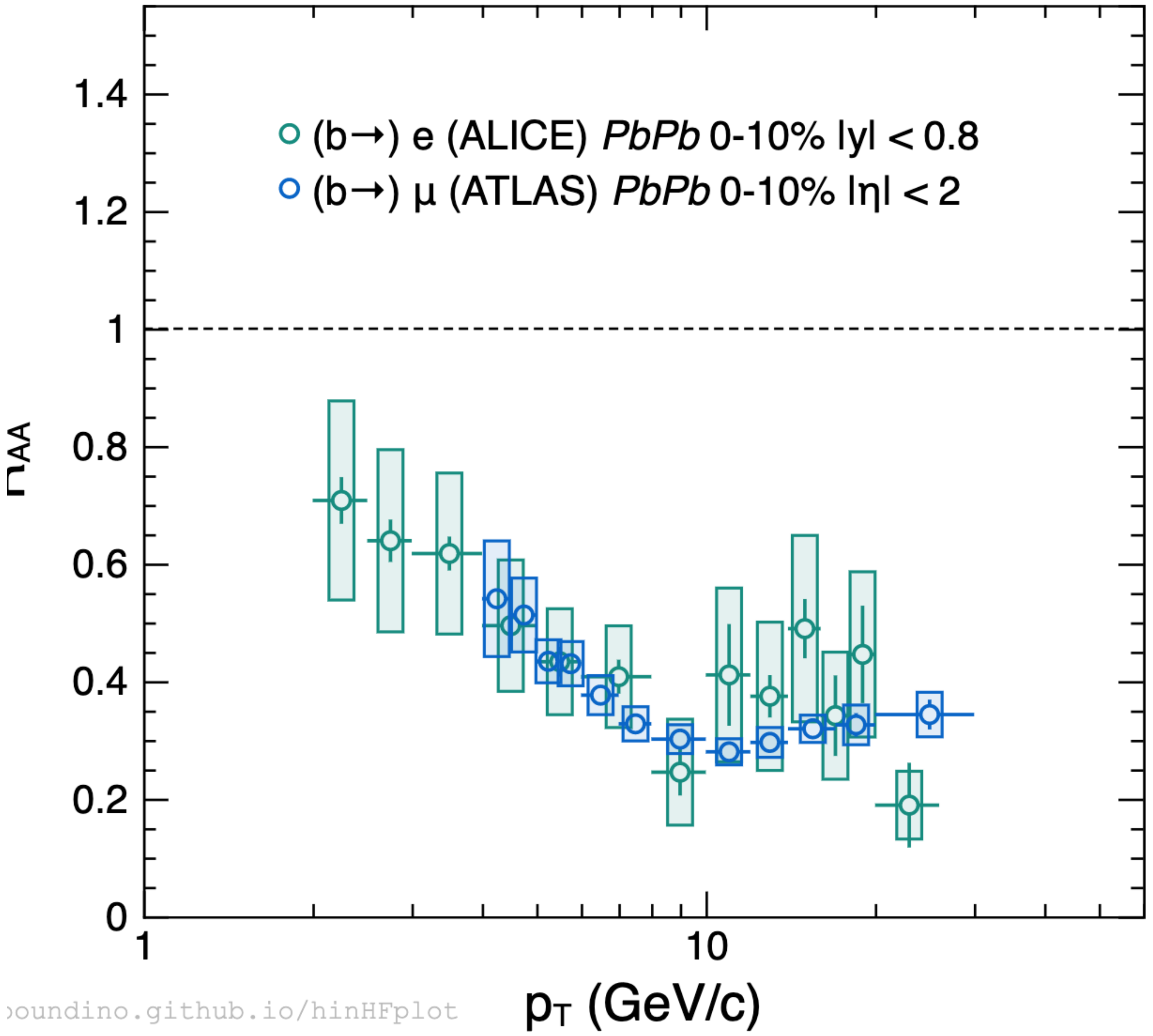
Cent. 0-100%



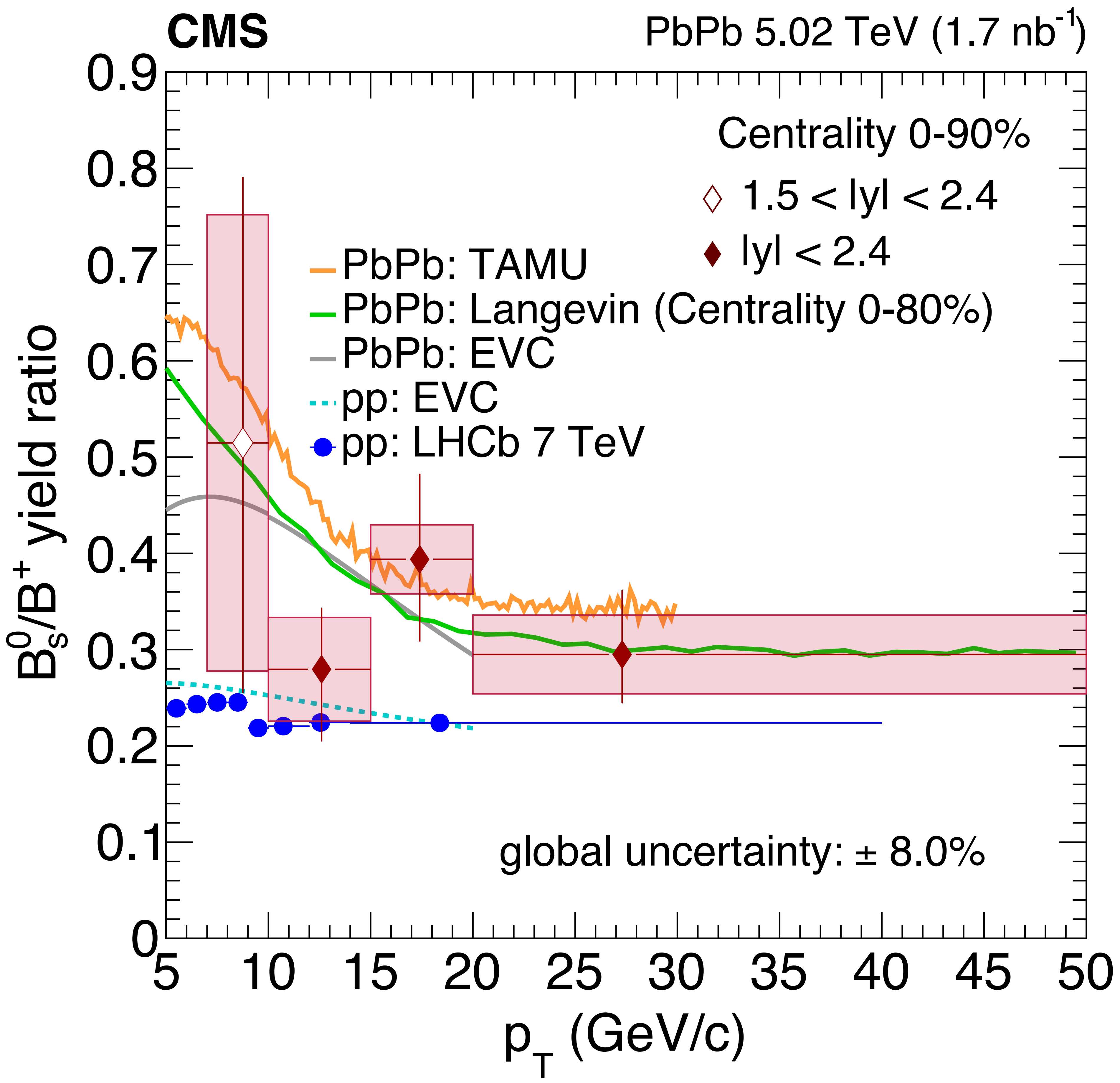
Cent. 0-10%



Cent. 0-10%



Strangeness Beauty Mesons in PbPb



CMS Phase-2 upgrades for HL-LHC

Table 1: Main features of CMS detector at present and Phase 2 upgrades.

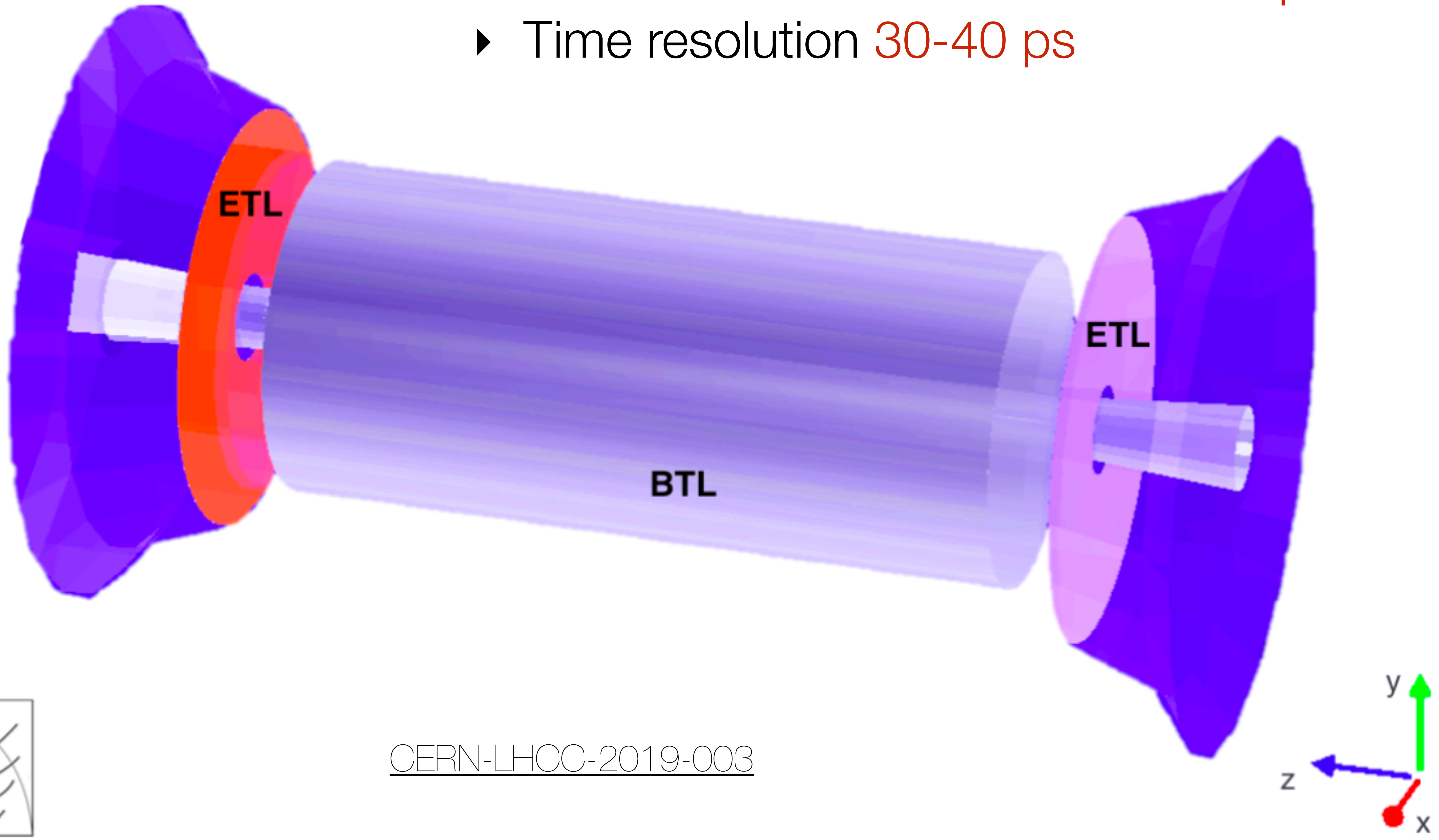
Subdetector	CMS present	CMS Phase-2
Inner Tracker	$\|\eta\| < 2.4$, $100\times150\ \mu m^2$ pixel size	$\|\eta\| < 4$, $50\times50\ \mu m^2$ pixel size
Calorimeter	Low-granularity	High-granularity end-cap with silicon sensors
Muon detector	$\|\eta\| < 2.4$	$\|\eta\| < 2.8$
L1 trigger bandwidth	30 kHz for PbPb, 100 kHz for pp and pPb	750 kHz (pass through all PbPb events)
DAQ throughput	6 GB/s	60 GB/s
Time-of-flight for Particle ID	**N/A**	**MTD for charged hadron PID over $\|\eta\| < 3.0$**

- New MIP Timing Detector (MTD) for TOF-PID!
- Unique PID up to |η| = 3

Precision determination of the arrival time of the signal

CMS MIP Timing Detector (MTD)

- Large acceptance
  - Barrel Timing Layer (BTL): |η| < 1.5
  - End-cap Timing Layer (ETL): 1.6 < |η| < 3
- Serve as TOF detector for hadron particle identification
- Time resolution 30-40 ps

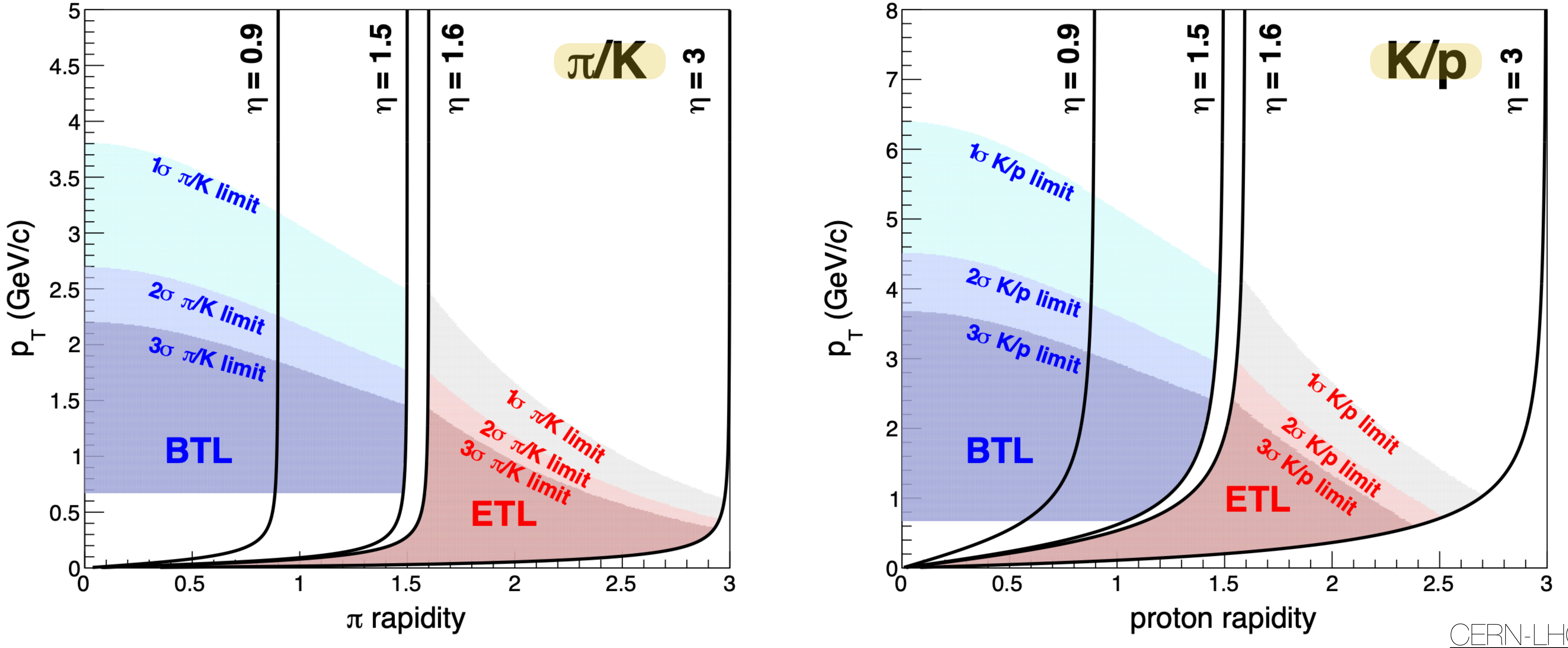


Experiment	r (m)	σ_T (ps)	r/σ_T ($\times 100$) ($\mathrm{m} \times \mathrm{ps}^{-1}$)
STAR-TOF	2.2	80	2.75
ALICE-TOF	3.7	56	6.6
CMS-MTD	1.16	30	3.87

CERN-LHCC-2019-003

CMS MIP Timing Detector (MTD)

Separation Power vs. kinematic phase space



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- CMS MTD brings complementarity and uniqueness in PID

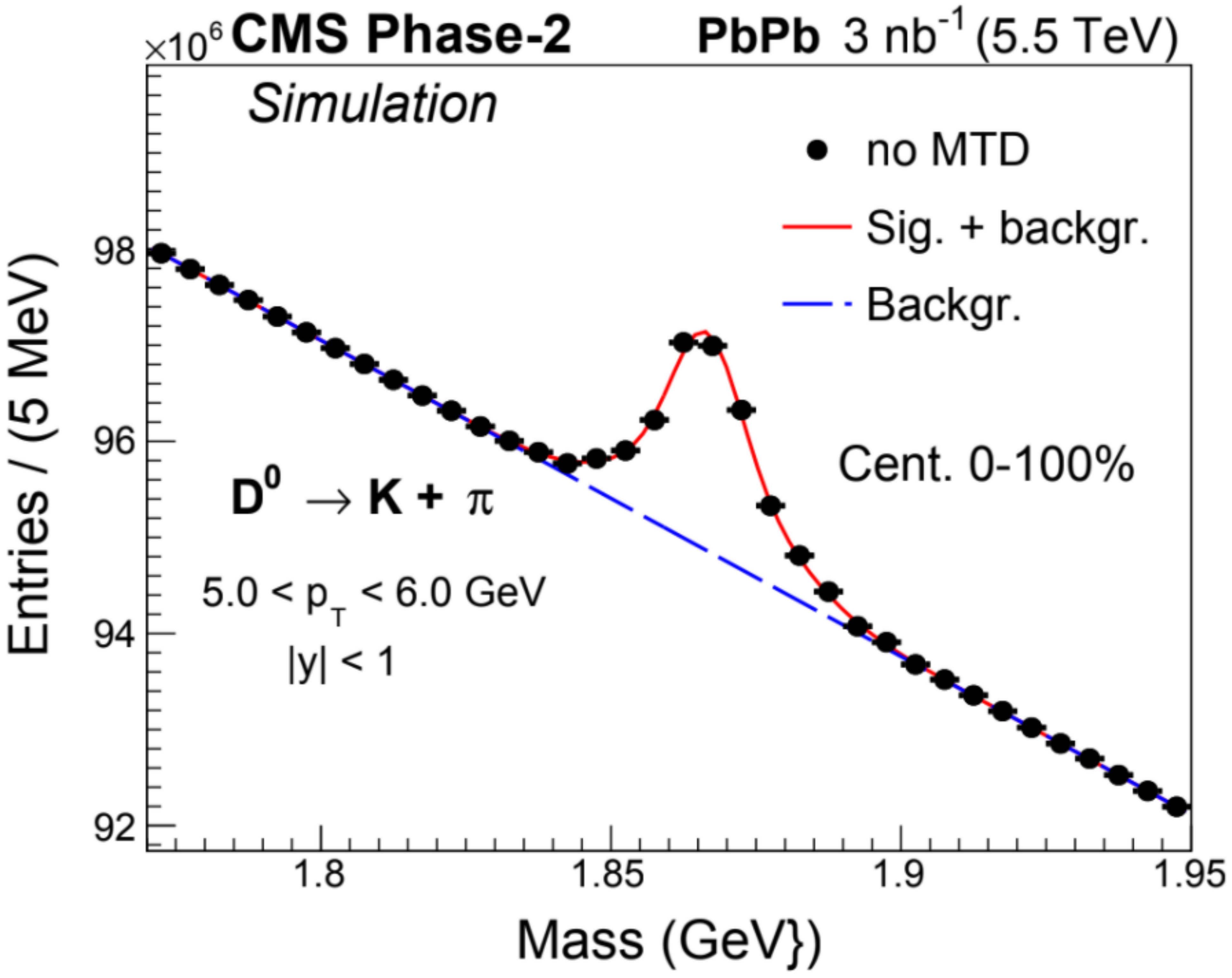
CMS MTD ($|\eta| < 3$) vs. ALICE: mid-rapidity ($|\eta| < 0.9$)
LHCb: forward ($2 < \eta < 5$)

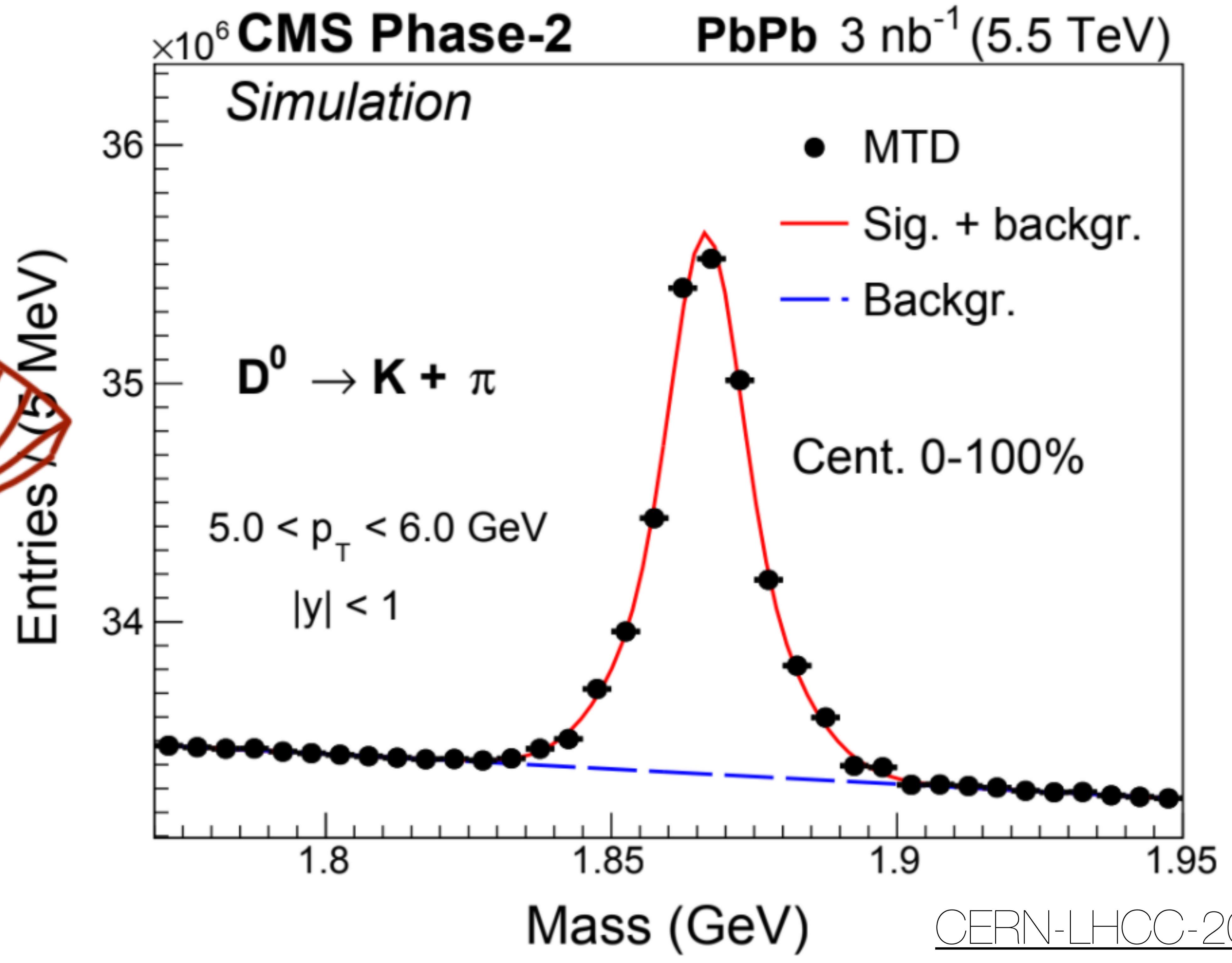
MTD Impact on HF hadron reconstruction

Without MTD

CMS 1 year of Run 4

With MTD





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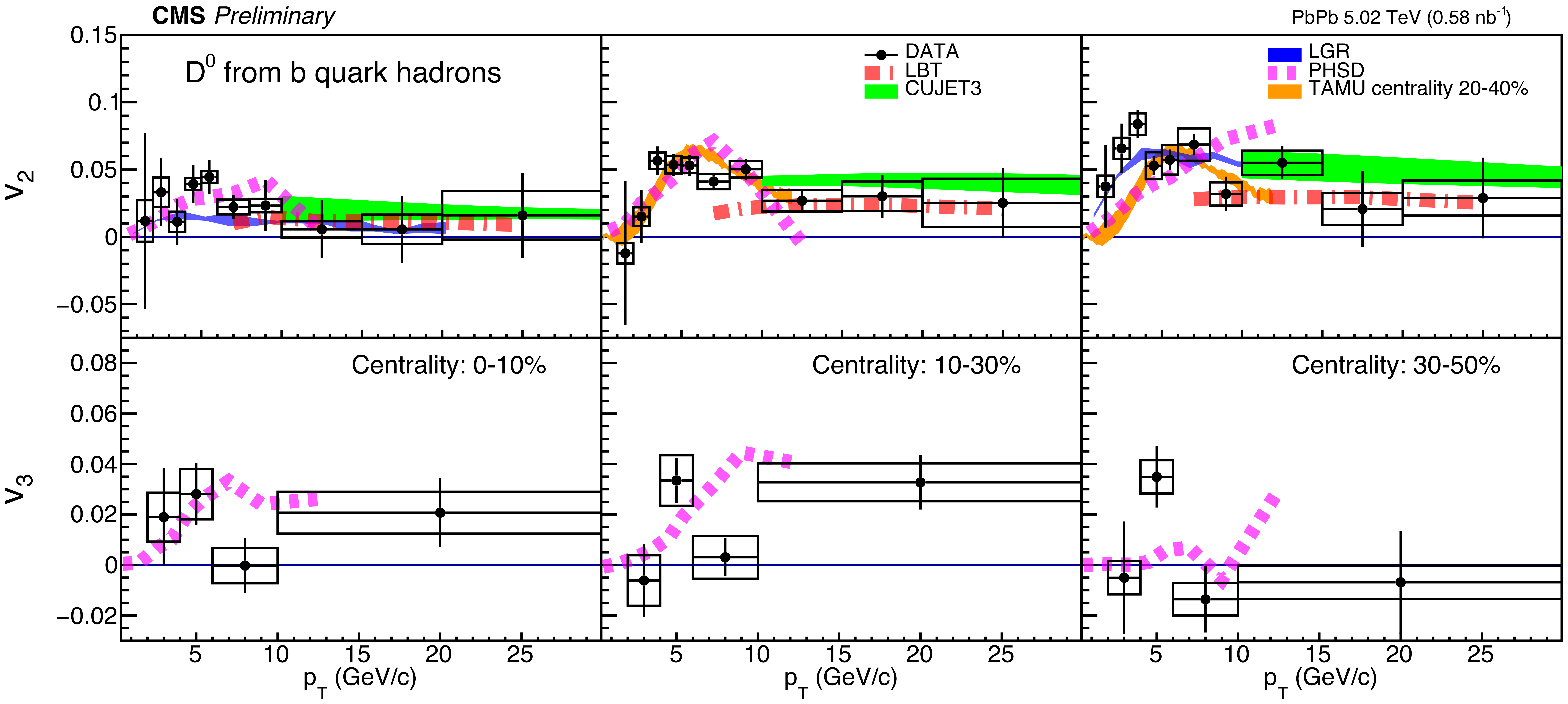
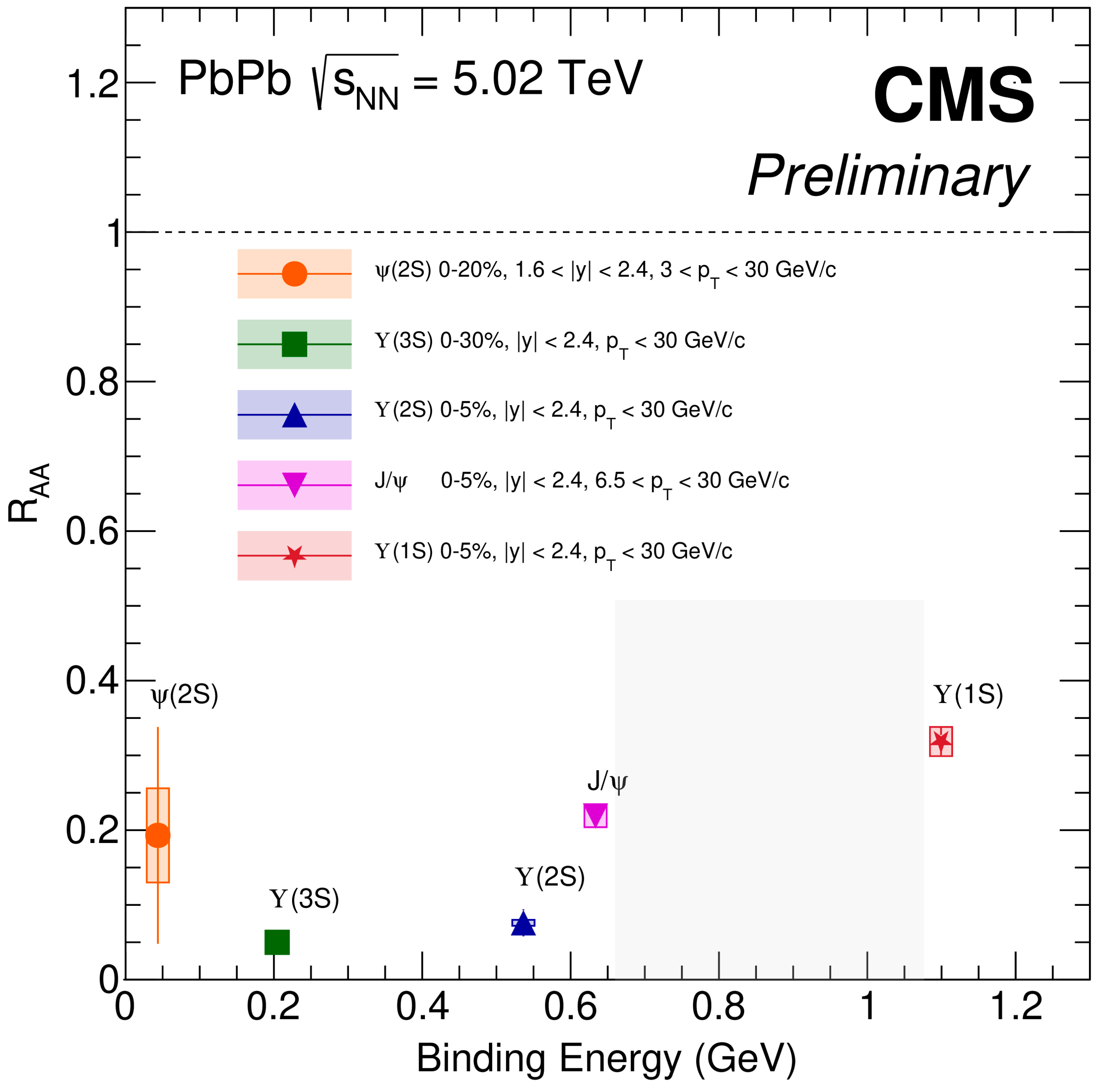
- Significant improvement of signal to background ratio with PID information from MTD

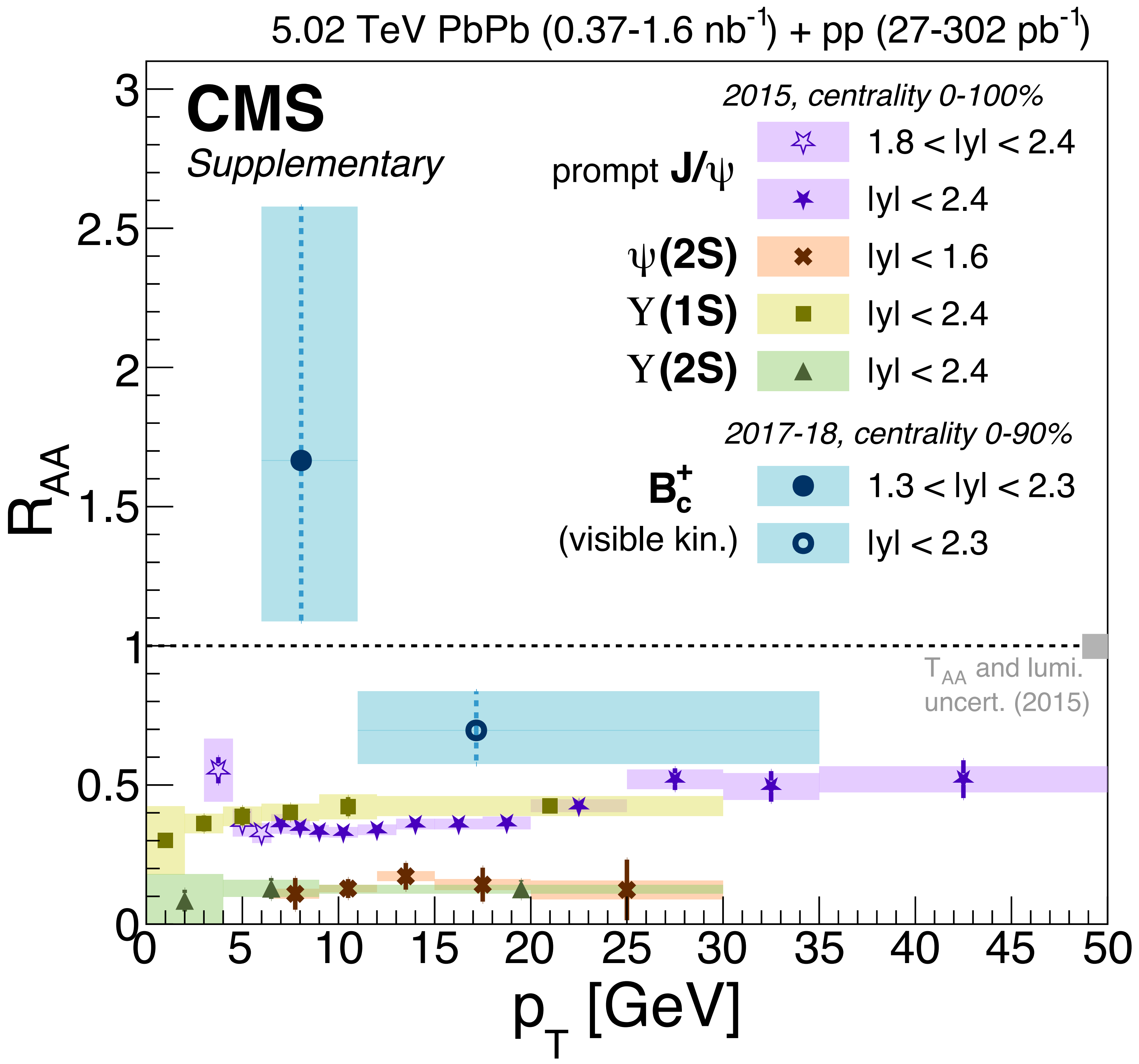
b→D v_n vs. Theory

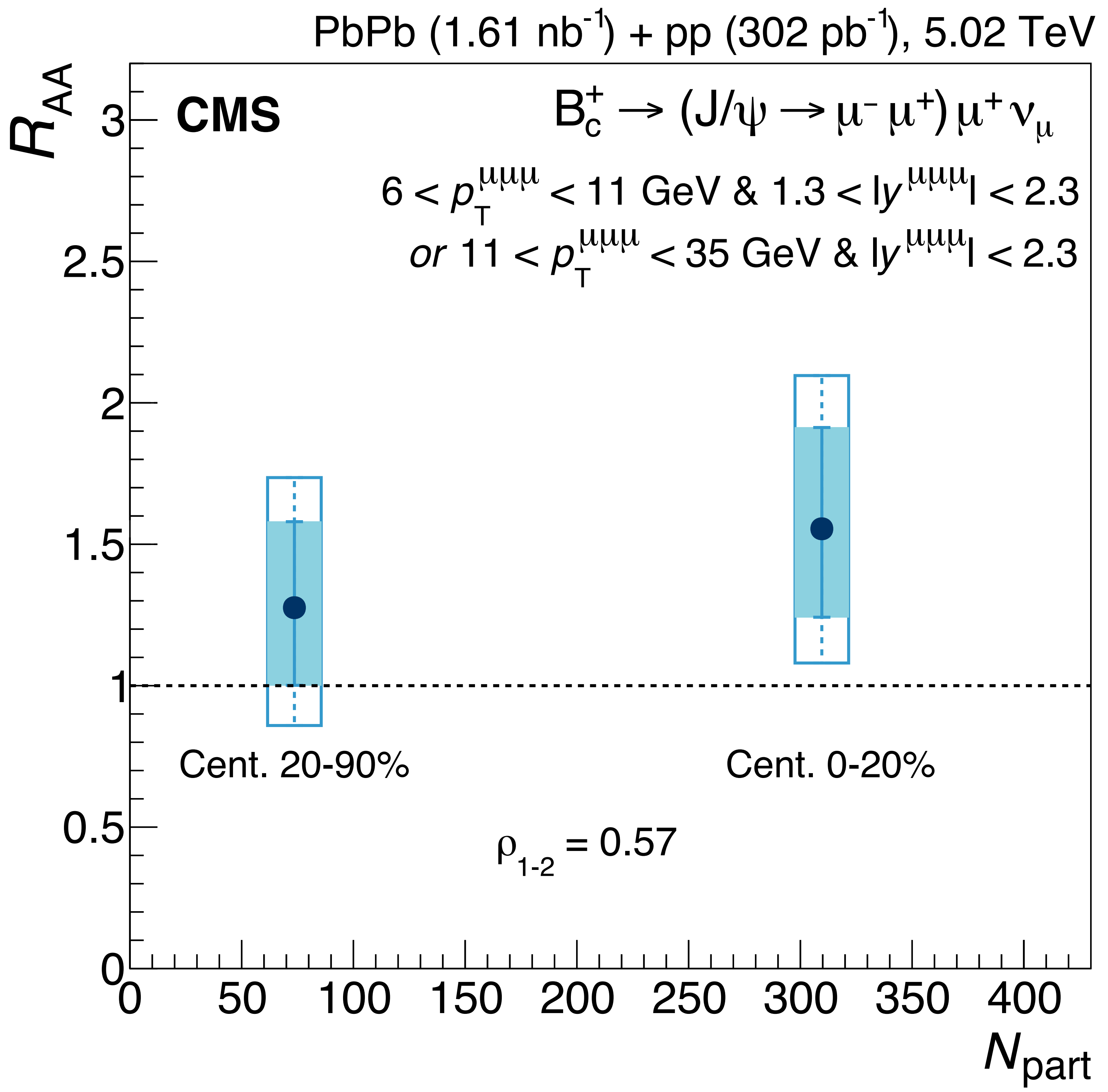


CMS-PAS-HIN-21-003

B_c in PbPb







B_c^+ less suppressed than quarkonia despite a binding energy between J/ψ and Υ(1S)

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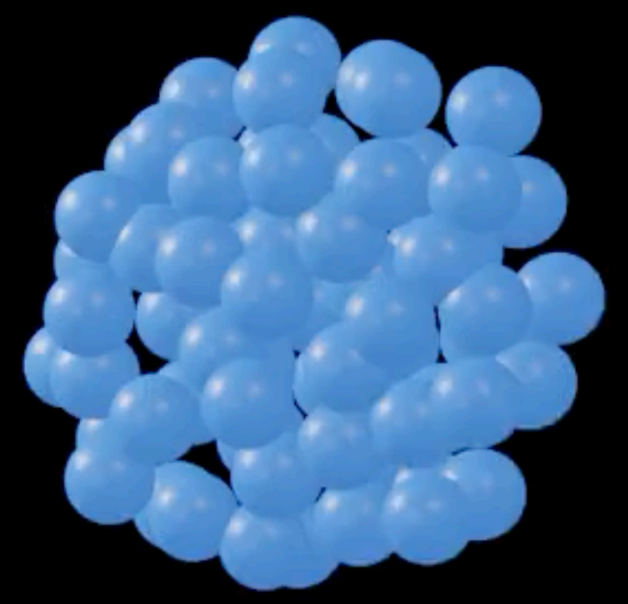
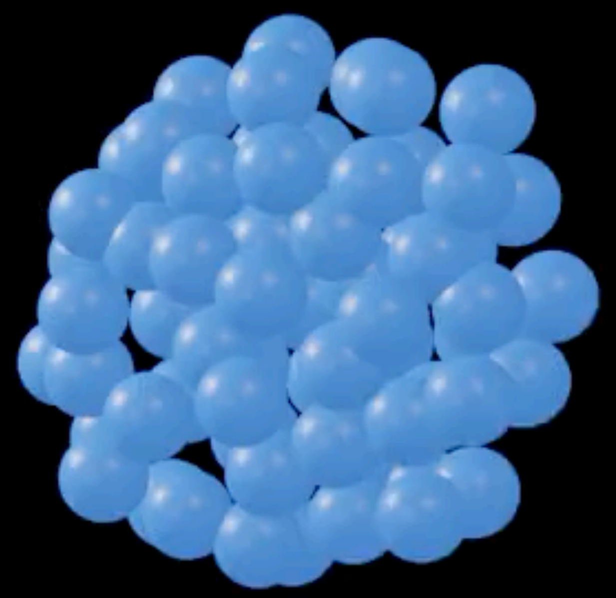
Section I

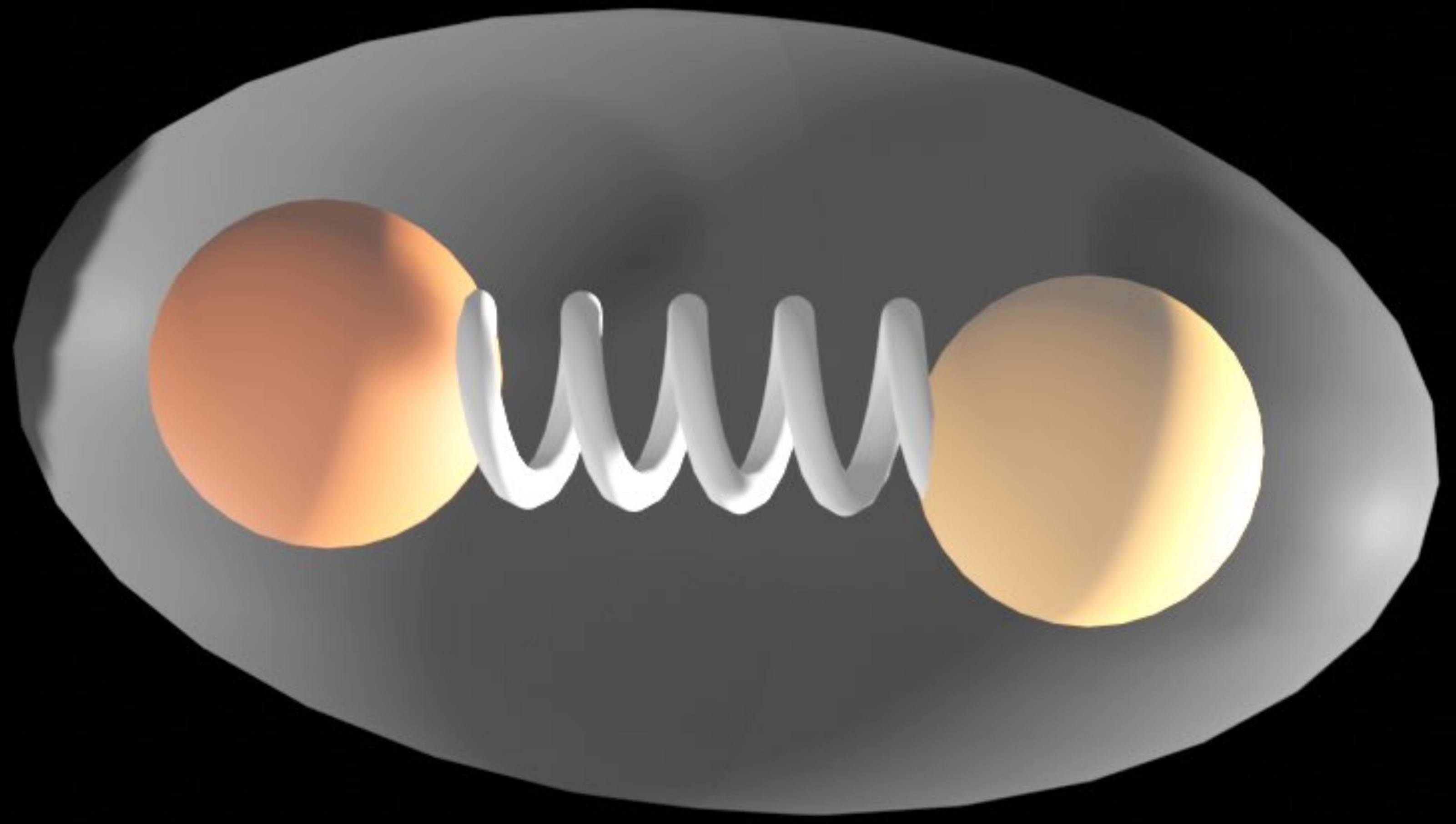
Section II



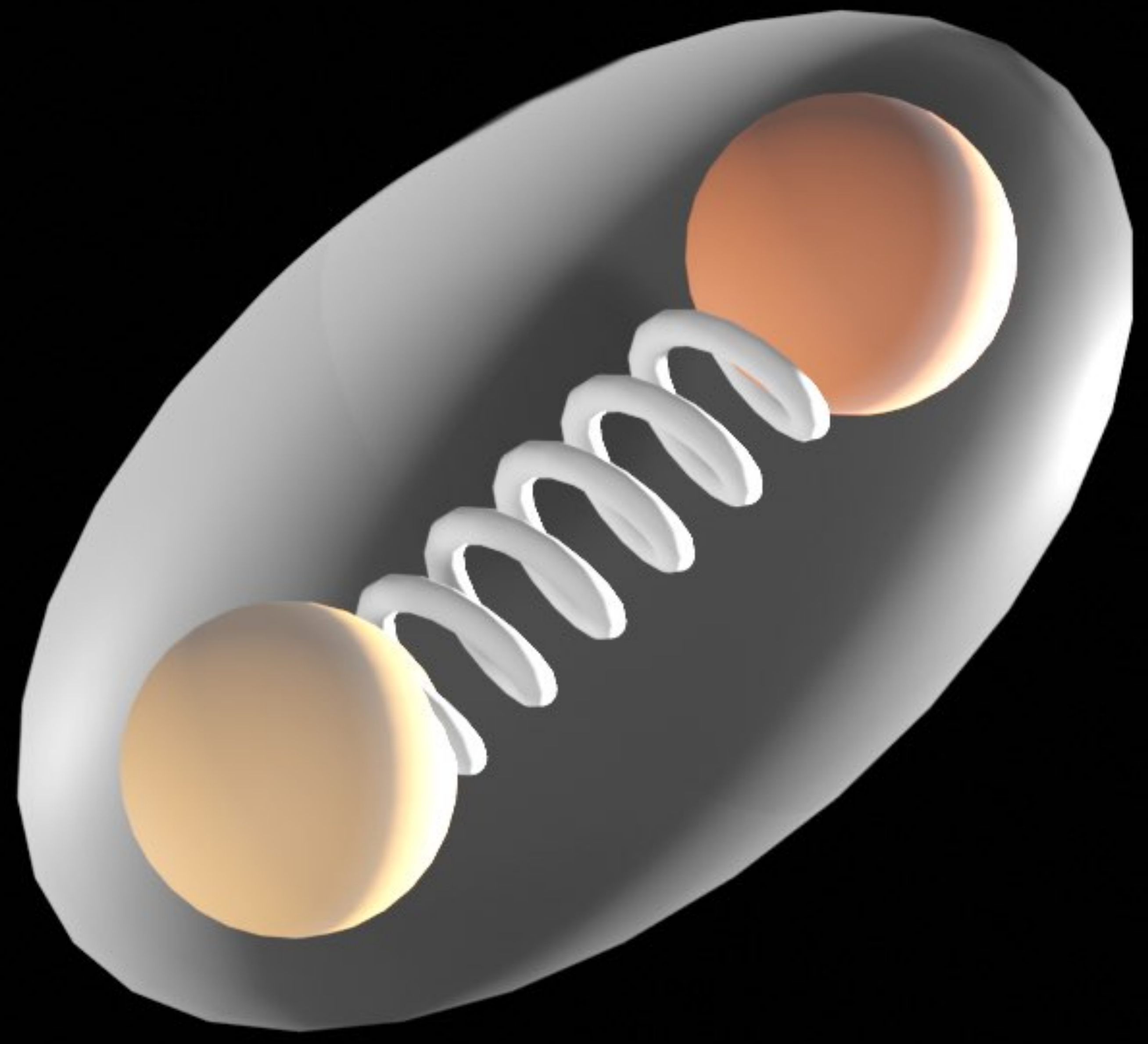
Section III



Section IV



Freeze-out & Rescatterings



Click to see animation ➥

Section V

Click to see animation ↪