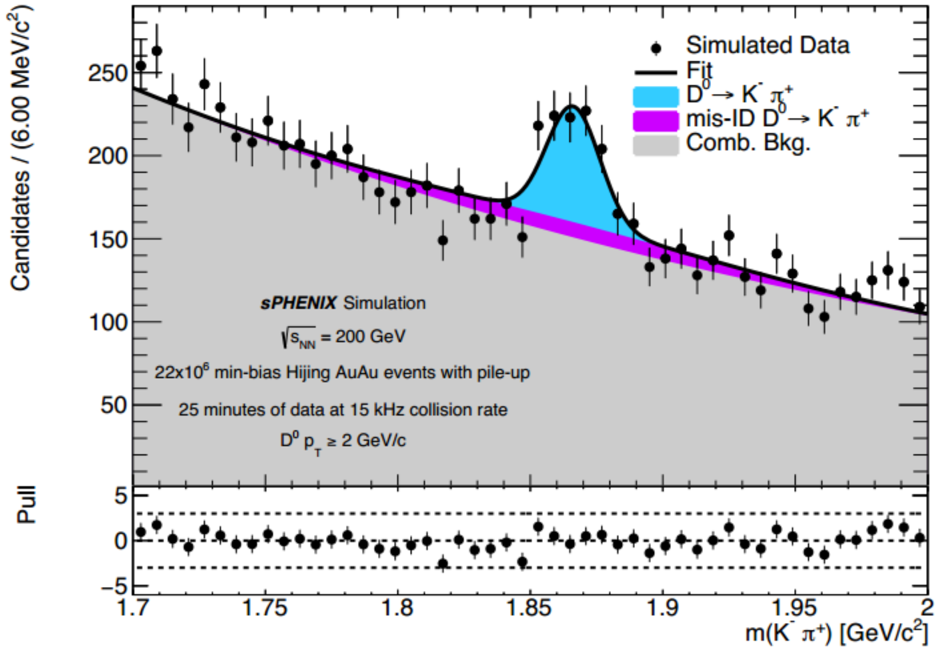
Heavy flavor measurements at QM2023

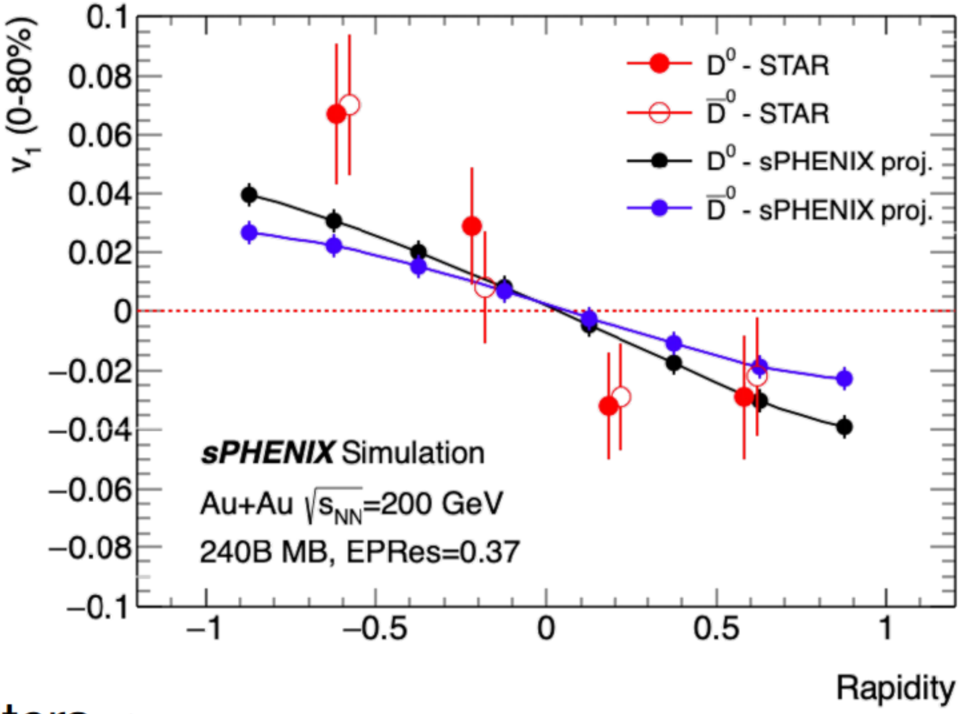
HI-9.26-suyuan

sPHENIX commissioning run started in May 18th

- First barrel HCal at RHIC for precise HF-jets
- Largest inclusive b-hadron sample at RHIC enabled by streaming readout

Open charm physics simulation



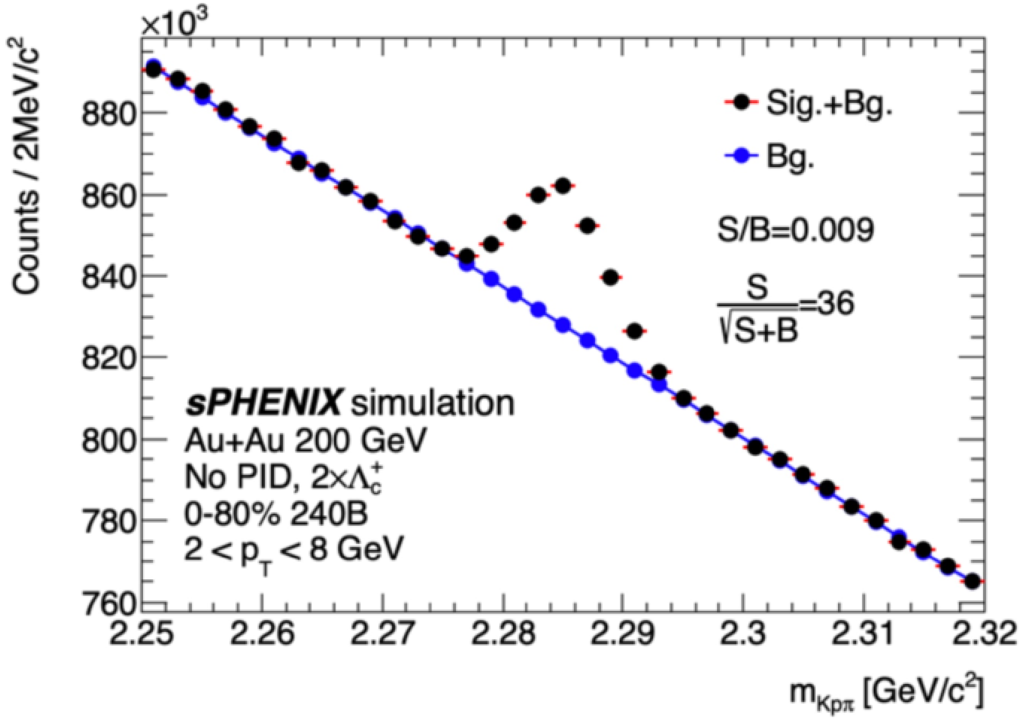


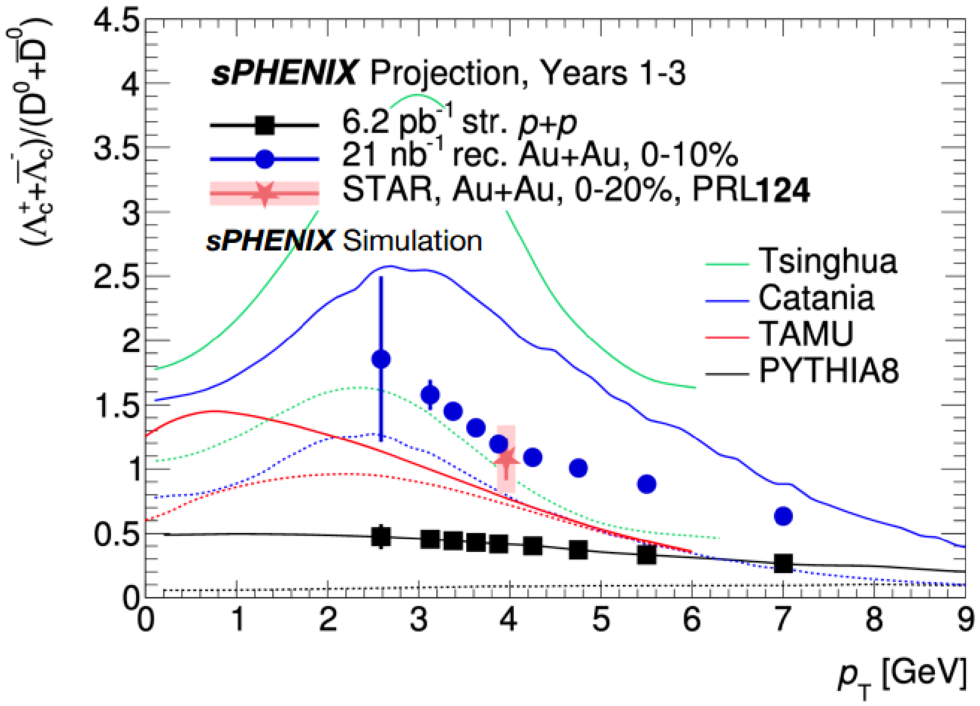
- Prediction that transient mag. field alters v_1
- This effect is odd under charge-conjugation, resulting in splitting
- $D^0 \to K^{\mp}\pi^{\pm}$ is mixed, requires good production knowledge

PRL 123 (2019) 162301
PRL 118 (2017) 212301

Cameron Dean
September 5th, 2023

Λ_c^+ coalescence simulation





Open Charm Hadron	Constitution
D^0	$c\bar{u}$
D^+	$c\bar{d}$
D_s^+	$c\bar{s}$
Λ_c^+	udc

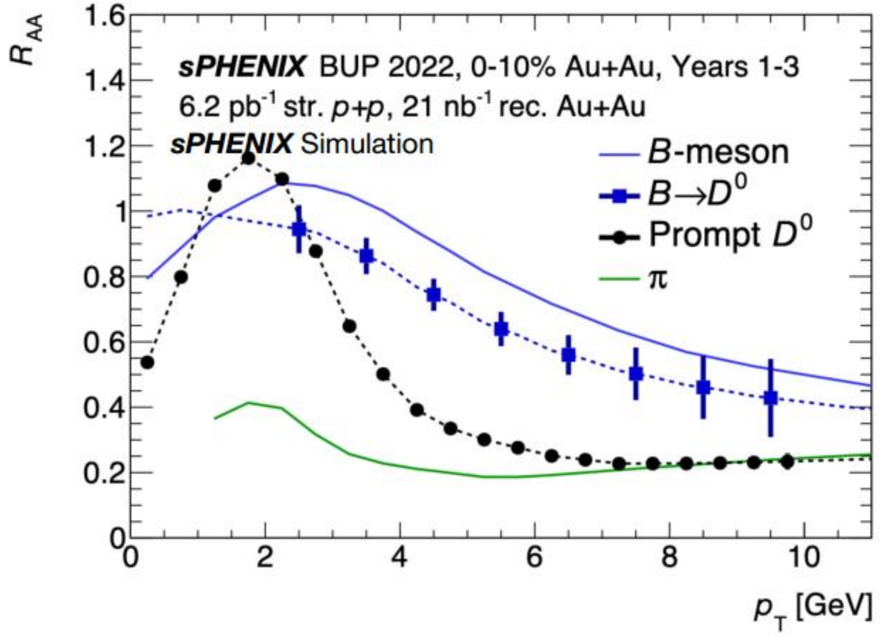
- Baryon/meson yields offer new insights in hadronization
- Models currently favor coalescence hadronization
- Low p_T region (< 8 GeV) is key
- Huge benefit from streaming readout in *pp*

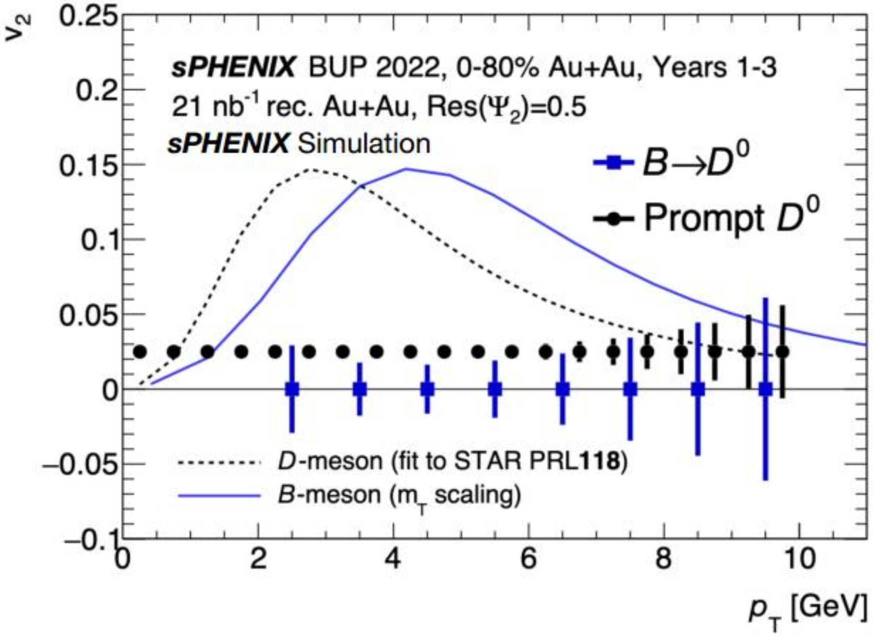
sPH-HF-2019-001

PRL 124 (2020) 172301

Cameron Dean
September 5th, 2023

b-hadron simulation

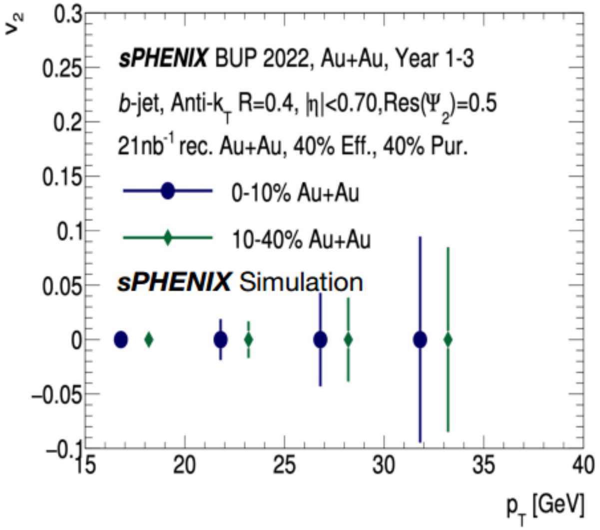




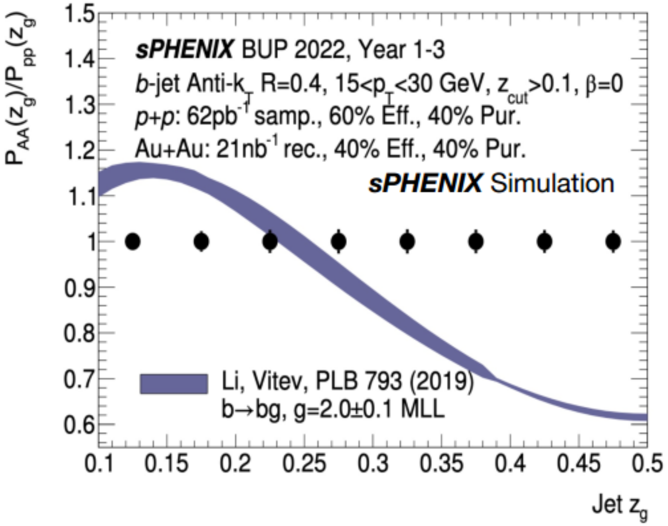
- Non-prompt D^0 reco. gives low p_T b-hadron access
- sPHENIX aims to
  - constrain heavy quark diffusion coefficients
  - Parton energy loss mechanism

PRL 118, 212301

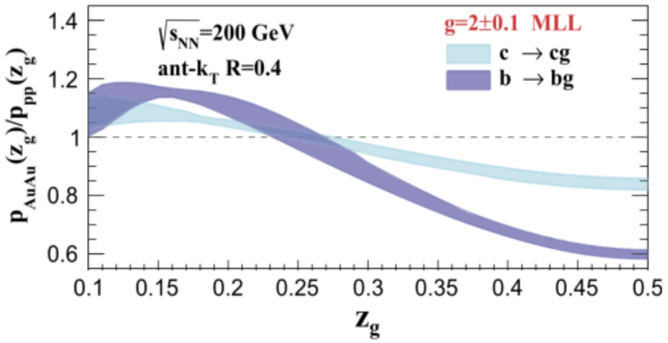
Heavy flavor jet observable simulation



b-jet elliptical flow



Predicted b-jet subjet splitting sensitivity



Model comparison of b- and c-jet subjet splitting sensitivity

Cameron Dean
September 5^{th}, 2023

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

$$p(z_g)\big|_j = \frac{1}{\sigma_j} \int dp_T d\eta \frac{d\sigma_j}{dp_T d\eta} \int_0^1 d\theta \; p(\theta, z_g)\big|_j$$

"We identify the region of jet transverse momenta where parton mass effects are leading and predict a unique reversal of the mass hierarchy of jet quenching effects in heavy ion relative to proton collisions. Namely, the momentum sharing distribution of prompt b-tagged jets is more strongly modified in comparison to the one for light jets."
- PLB 793 (2019)

Quarkonia & Heavy Flavor Overview

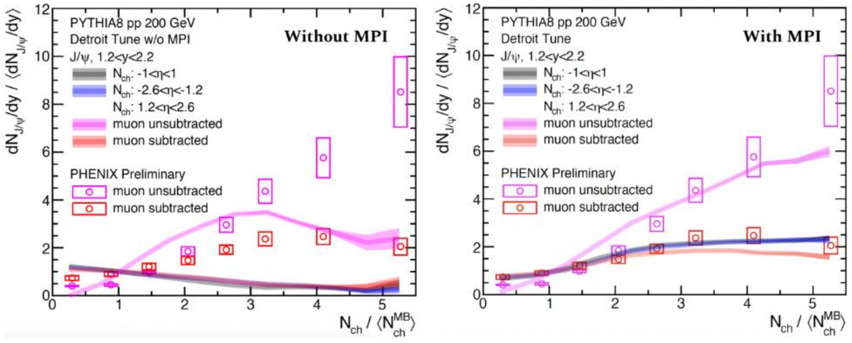
PHENIX

Three recent PHENIX analyses focus on the following collision systems and investigate the following:

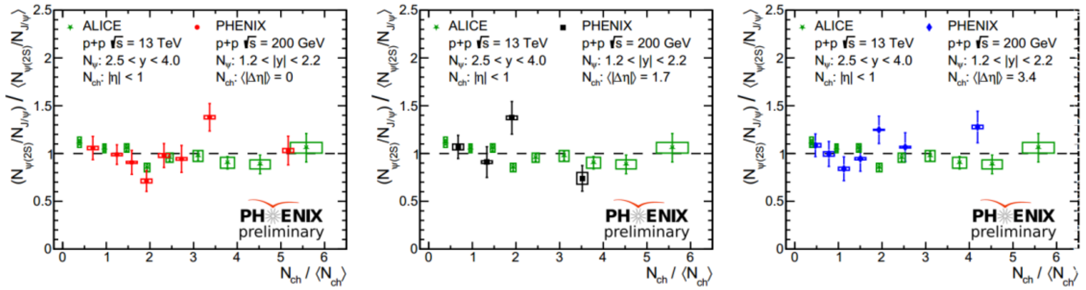
- 2013 $p+p$ at $\sqrt{s} = 510$ GeV
- 2014 ^{3}**He+Au**, **Au+Au** at $\sqrt{s_{NN}} = 200$ GeV
- 2015 $p+p$, $p+$**Al**, $p+$**Au** at $\sqrt{s_{NN}} = 200$ GeV
- 2016 $d+$**Au**, **Au+Au** at $\sqrt{s_{NN}} = 200$ GeV

1. Do we see evidence for multi-parton interactions at RHIC energies?
2. Are there final state effects on charmonium production in $p+p$ collisions?
3. Is there evidence of mass ordering for charged hadron vs. open heavy flavor v_2?

Multiplicity Dependent J/ψ Production



Multiplicity Dependent $\psi(2S)$ to J/ψ



Small System Collisions — $p+p$

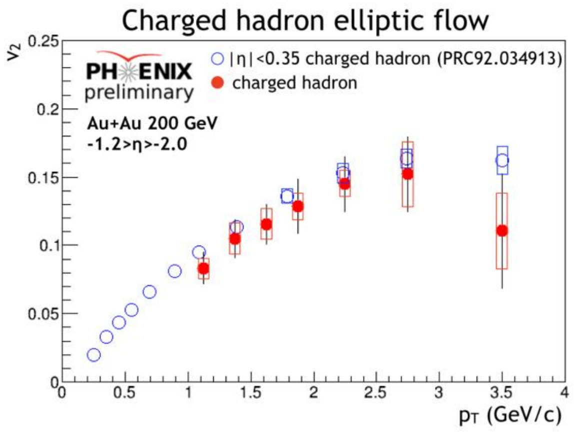
- Multiplicity dependent J/ψ varies based on η of charged particle tracks
  - PHENIX data well described by PYTHIA Detroit tune with MPI
  - $\Longrightarrow$ Evidence for MPI at RHIC energies

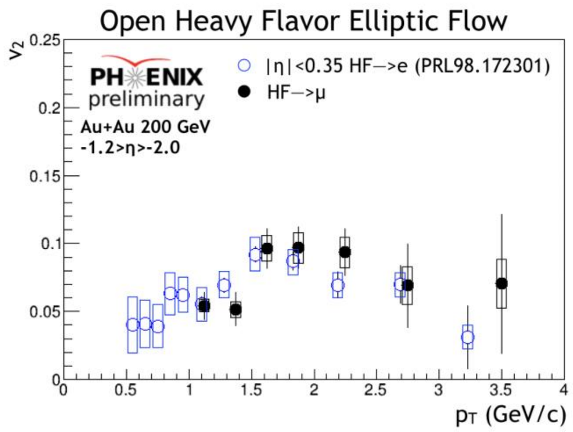
Consistent with ALICE

- $\psi(2S)$ to J/ψ ratio in $p+p$ collisions shows weak dependence on multiplicity
  - $\Longrightarrow$ No evidence for $\psi(2S)$ final state effects in $p+p$ collisions at RHIC

Large System Collisions — A+A

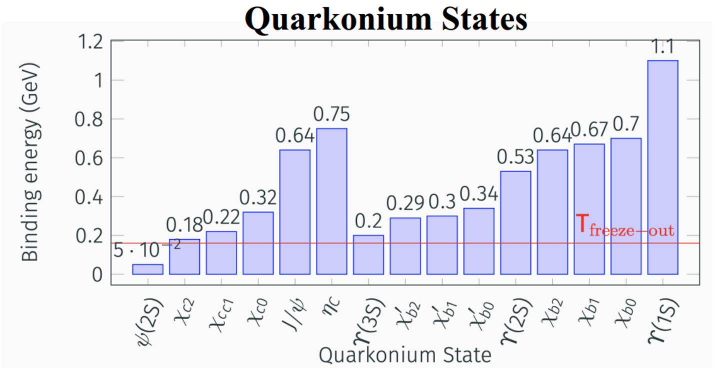
- First RHIC measurement of open heavy flavor v_2 at forward rapidity
  - Results consistent with PHENIX mid-rapidity measurements, suggesting similar QGP effects (temperature/pressure gradients) at both rapidities
  - $\Longrightarrow$ Mass ordering observed at forward rapidity





Krista Smith
September 5th, 2023

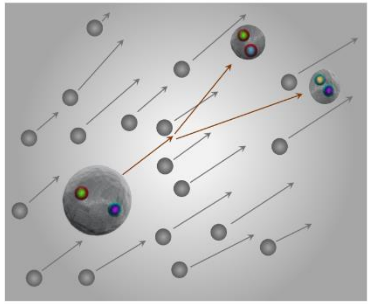
New LHCb results on quarkonia production (and exotic hadron) in pp and pPb collisions.



If medium is formed and temperature is above its binding energy, the quarkonium state is inhibit to be produce.

$T_{freeze\text{-}out}$ ~ 155-160 MeV

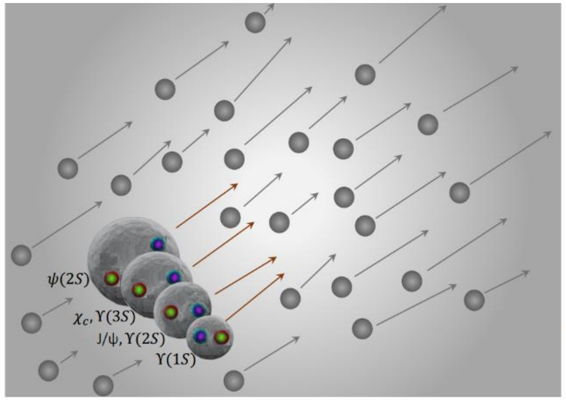
Lattice QCD A. Bazavov et al., PLB795 (2019) 15
Thermal Model N. Sharma et al. PRC 99 (2019) 044914
Thermal fits to ALICE data F. A. Flor, PLB 834 (2022) 137473



Alternative way to break quarkonium states:

Large quarkonium states can break in high-multiplicity environment when interacting with **co-moving** particles

[Ferrero, PLB749, 98 (2015)].

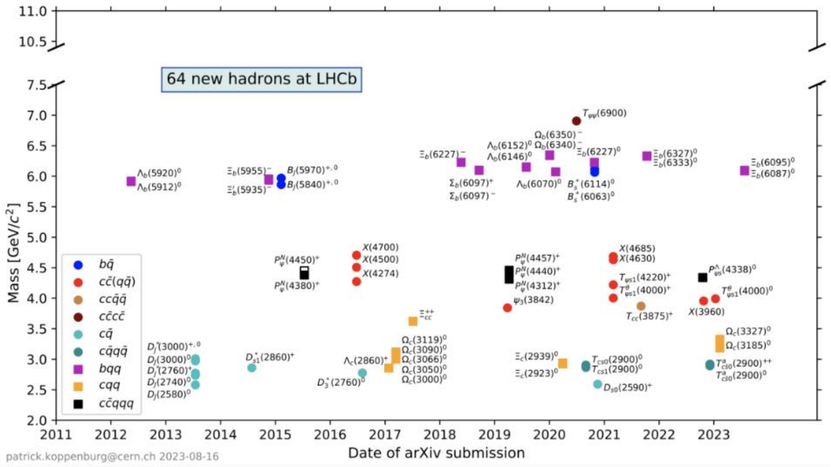


	$r(fm)$
J/ψ	0.50
χ_c	0.72
$\psi(2S)$	0.90
$\Upsilon(1S)$	0.28
χ_b	0.44
$\Upsilon(2S)$	0.56
$\chi_b(2P)$	0.68
$\Upsilon(3S)$	0.78

Non-Relativistic Potential Theory: Satz, J.Phys.G32:R25 (2006)

Cesar Luiz da Silva
September 5th, 2023

Exotic Particles

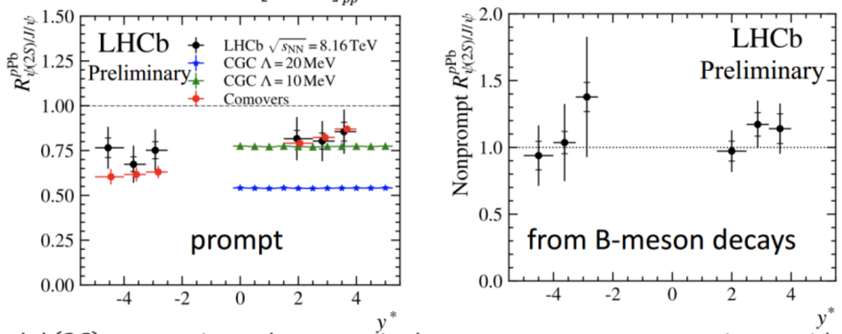


https://www.nikhef.nl/~pkoppenb/particles.html

New ψ(2S) Result at $\sqrt{s_{NN}}$=8.16 TeV

$$R^{pPb\,(Pbp)}_{\psi(2S)/J/\psi} = \frac{R_{pPb\,(Pbp)}(\psi(2S))}{R_{pPb\,(Pbp)}(J/\psi)} = \frac{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{pPb\,(Pbp)}}{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{pp}}$$

LHCb-PAPER-2023-024 in preparation

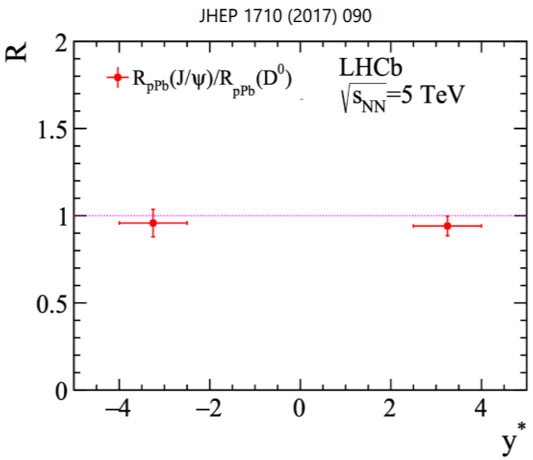


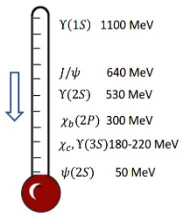
Additional $\psi(2S)$ suppression only present in the prompt component, consistent with co-mover particle interactions [PLB749, 98 (2015)]

CGC : Factorization violating soft gluon exchanges PRC97, 014909 (2018)

"Now we know how to use the quarkonium thermometer"

Agnes Mocsy's thermometer





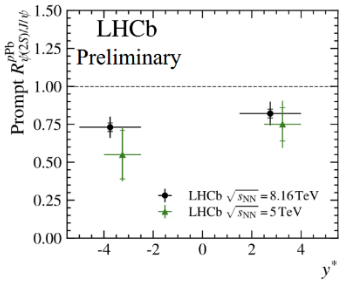
Initial-state effects are cancelled out in the $R_{pA}(J/\psi)/R_{pA}(D^0)$ ratio.

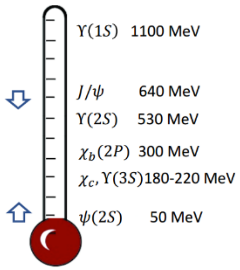
J/ψ yield is not affected by final-state effects.

New $\psi(2S)$ Result at $\sqrt{s_{NN}}$=8.16 TeV

$$R^{pPb\,(Pbp)}_{\psi(2S)/J/\psi} = \frac{R_{pPb\,(Pbp)}(\psi(2S))}{R_{pPb\,(Pbp)}(J/\psi)} = \frac{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{pPb\,(Pbp)}}{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{pp}}$$

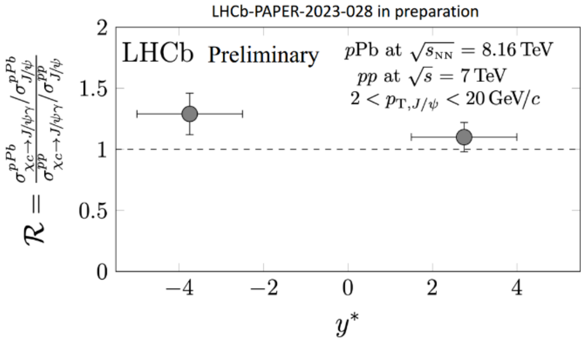
LHCb-PAPER-2023-024 in preparation

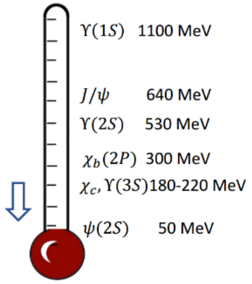




8.16 TeV result more precise and consistent with 5 TeV.

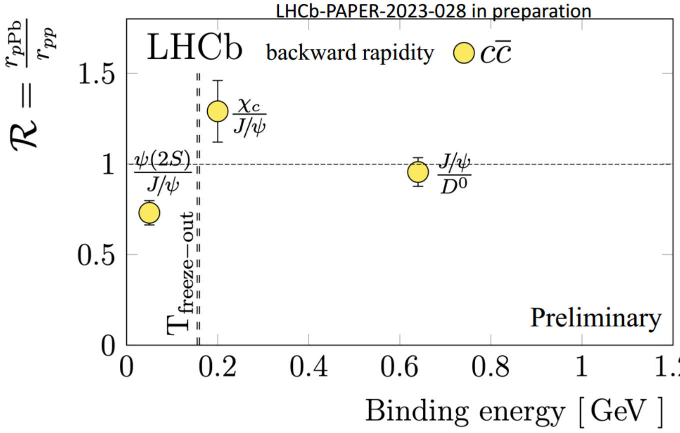
Confirming the existence of final-state effects on the $\psi(2S)$ yields.

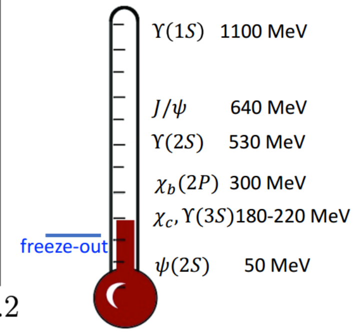




χ_c double ratio consistent with **NO final-state dissociation of χ_c states in pPb collisions**.

Constraints to maximum medium temperature in pPb collisions.

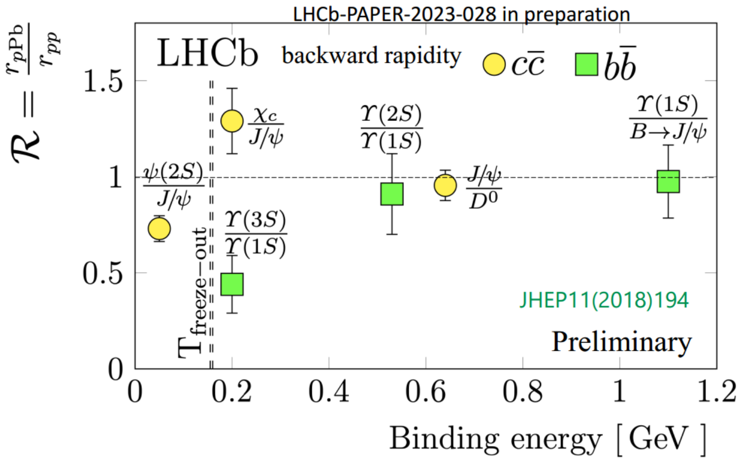




The medium temperature hypothetically formed in pPb collisions cannot inhibit the formation of charmonium states with binding energy larger than 180 MeV, just 20 MeV above the estimated freeze-out temperature.

18

Limiting the medium temperature in this `small system close of a hadron environment`



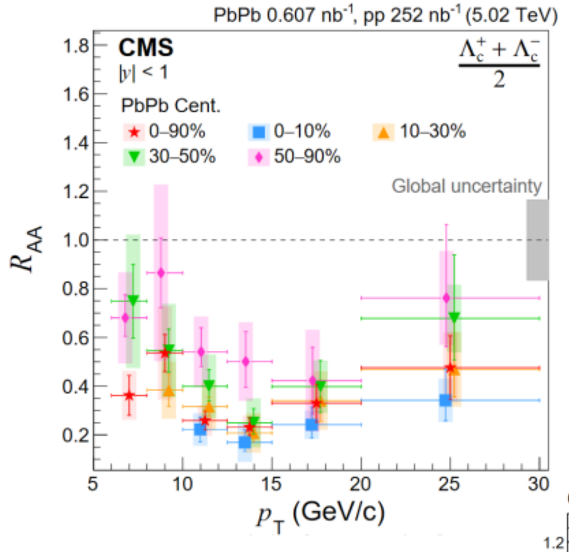
Despite the similar binding energy and size with χ_c, $\Upsilon(3S)$ is dissociated.

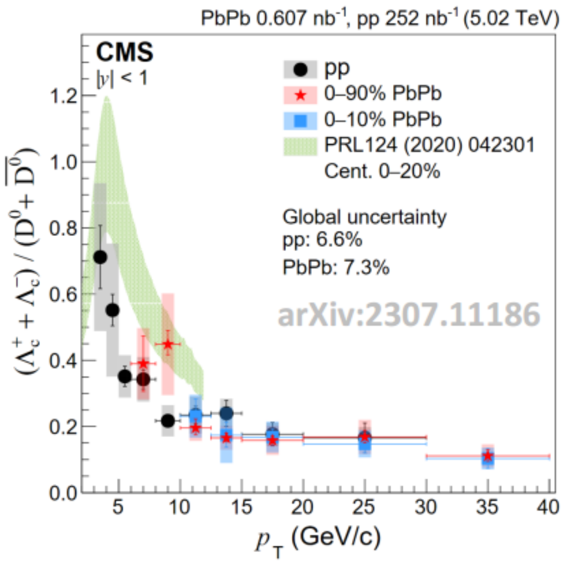
$\Upsilon(3S)$ is 2.9 x heavier and slower than χ_c, more likely to interact with comoving particles.

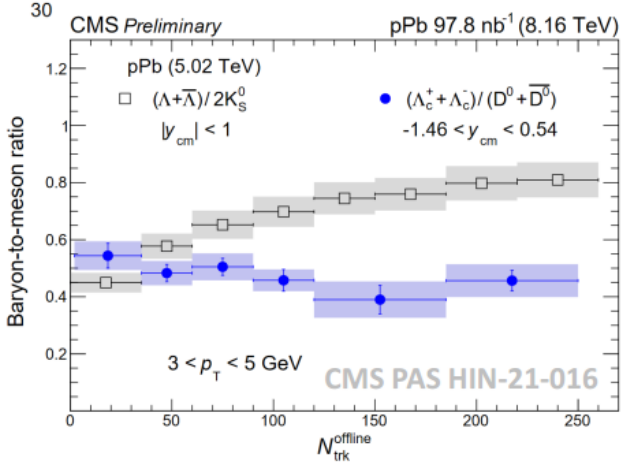
Theoretical input is welcome !!!

Cesar Luiz da Silva
September 5th, 2023

- ❑ Λ_c^+ production significantly suppressed in PbPb → charm quark E-loss
- ❑ Λ_c^+ production in pp collisions systematically higher than GM-VFNS calculation (hadronization tuned with e^+e^- data)
  - ➢ Breakdown of the universality of charm quark fragmentation functions?
- ❑ For $p_T > 10$ GeV/c, the Λ_c^+/D^0 ratios for pp and PbPb collisions are consistent, suggesting no significant contribution from coalescence to Λ_c^+ hadronization.
  - ➢ Λ_c^+/D^0 ratios for pp and PbPb converge with e^+e^- for $p_T > 10$ GeV/c
- ❑ No significant multiplicity dependence is observed for charm hadron production in pPb collisions
  - ➢ Different from strange quark, suggests coalescence processes of heavy quarks saturate earlier







Soumik Chandra
September 5th, 2023

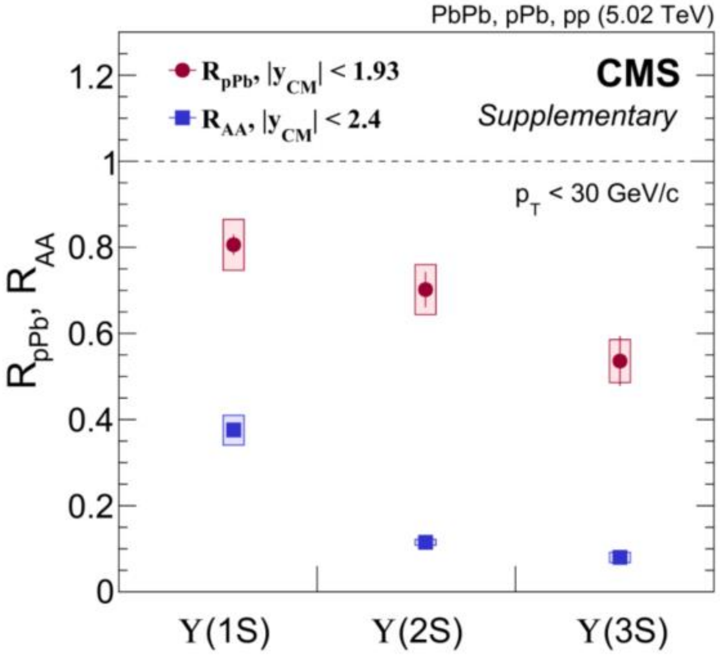
- Excellent performance for muon detection by the CMS experiment

CMS-PAS-MUO-21-001

  - Across pp, pPb and PbPb collisions, and wide range of detector occupancies

- Υ states in pPb collisions
  - Sequential ordering of suppression
    $R_{pPb}(1S) > R_{pPb}(2S) > R_{pPb}(3S)$
    - Follows their binding energies
    - Challenging to describe with initial state effects alone

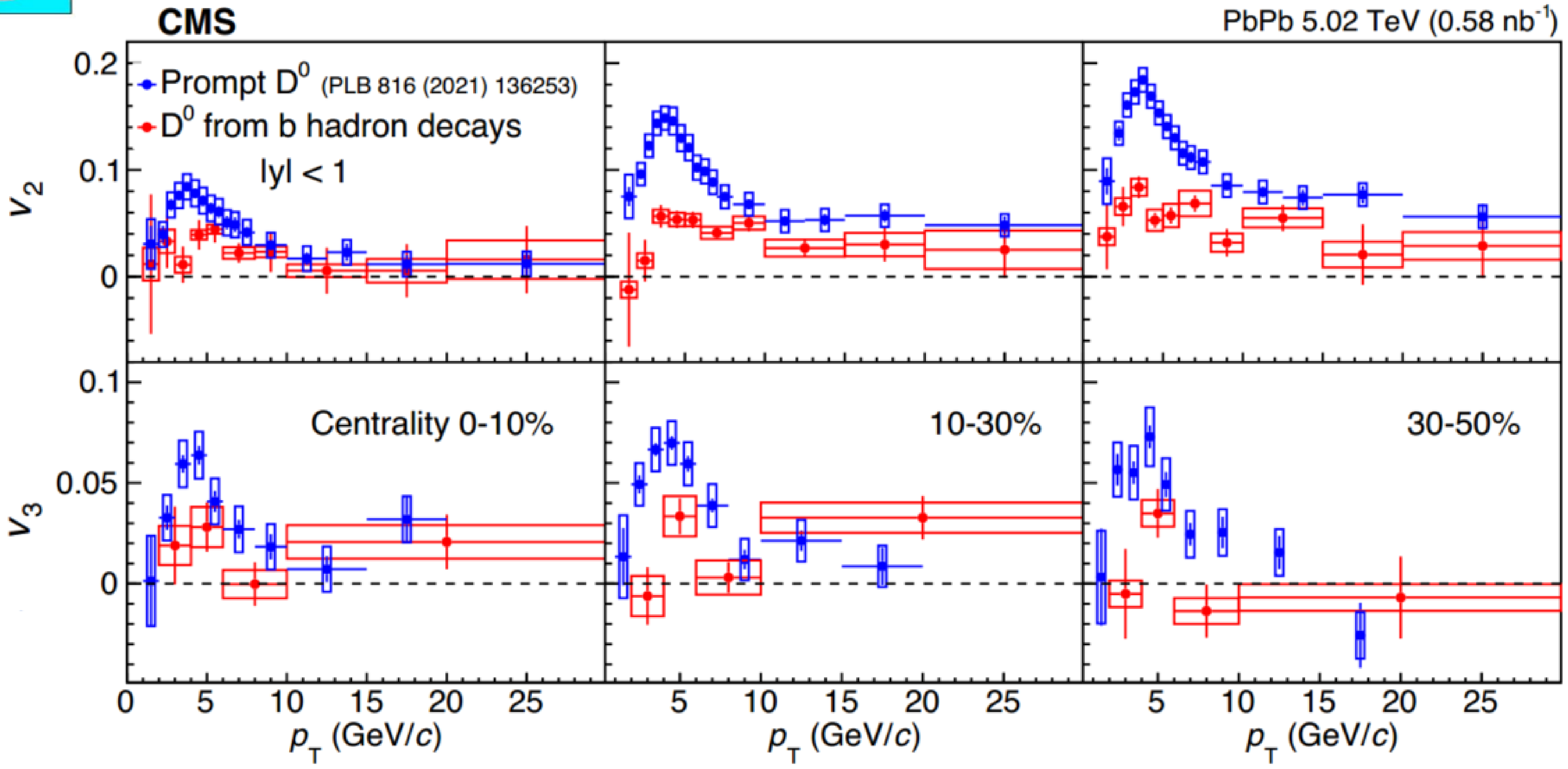
- First measurement of Υ(3S) in PbPb collisions
  - $R_{PbPb}(3S)$ = 0.080 ± 0.014 (stat) ± 0.012 (syst)
  - Same ordering as in pPb: $R_{PbPb}(1S) > R_{PbPb}(2S) > R_{PbPb}(3S)$
  - Overall suppression much larger than in pPb



PbPb (2S) and (3S) arXiv 2303.17026

pPb: PLB 835(2022), 137397

Ota Kukral
September 6th, 2023



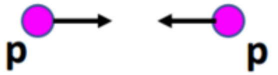
- Strong p_T and centrality dependence
- Significant nonzero v_3 up to ~10 GeV

VS

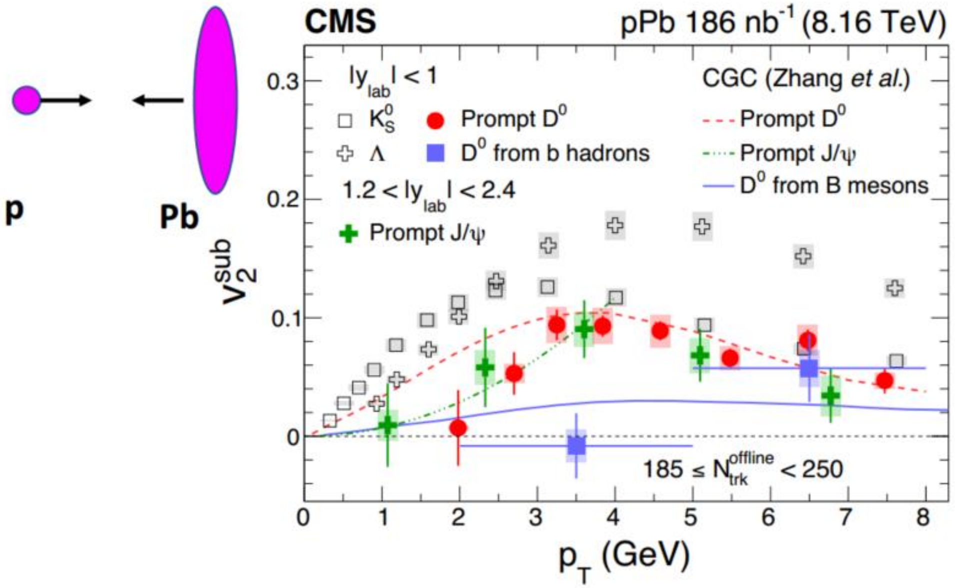
- ~~Strong~~ Weak p_T and centrality dependence
- ~~Significant~~ Indication of nonzero v_3

- Mass ordering of flow magnitudes

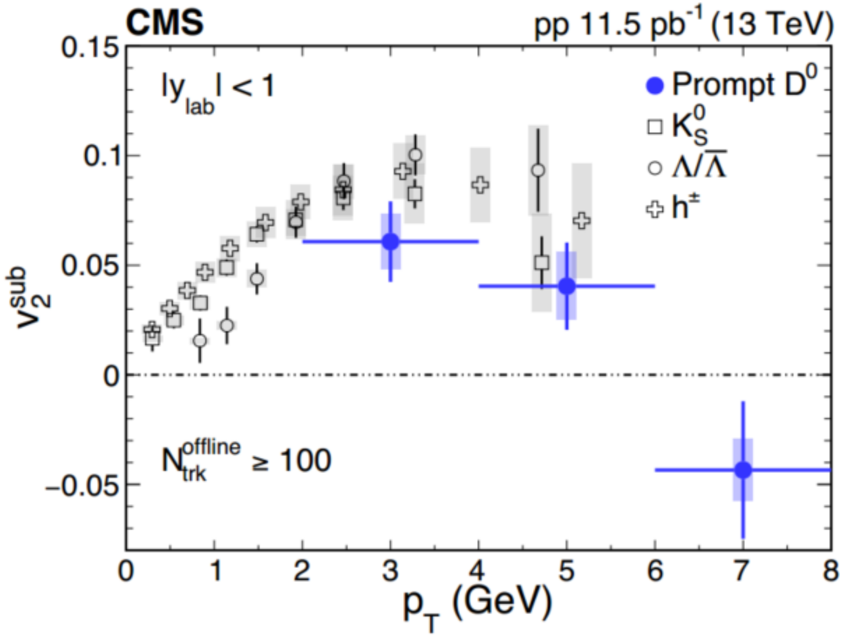
D^0 flow in small systems



- Open charm (prompt D^0) $v_2 \approx$ hidden charm (prompt J/ψ)
- Flavor hierarchy prompt D^0 $v_2 > b \rightarrow \mathrm{D}^0$ $v_2 \approx 0$
- In agreement with CGC model



- prompt D^0 v_2 compatible with light hadrons



PLB 813 (2021) 136036

- Significant prompt D^0 flow in small systems

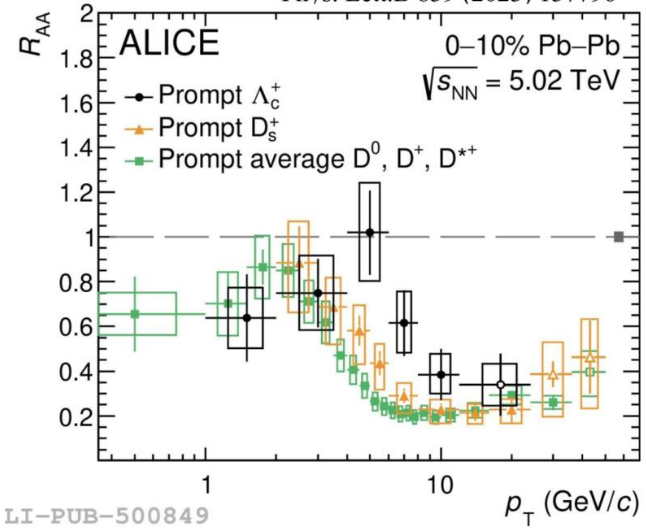
Mass ordering observed for $p_{\mathrm{T}} < 10$ GeV
- Both flow and R_{AA}
- Both PbPb and pPb

PLB 782 (2018) 474
PRL 123 (2019) 022001

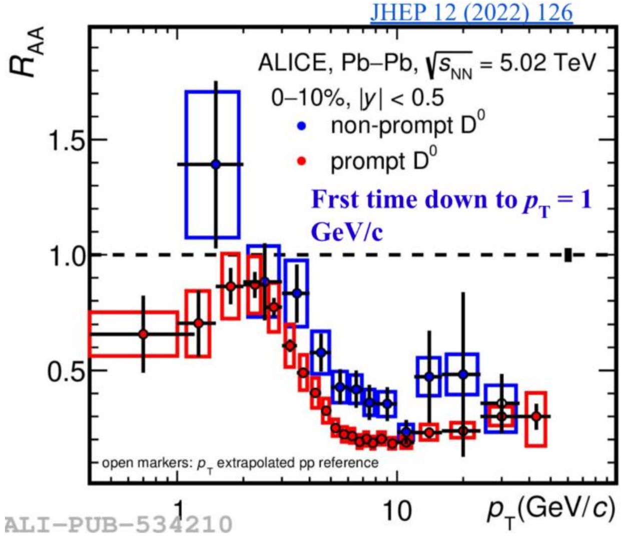
Milan Stojanovic September 6th, 2023

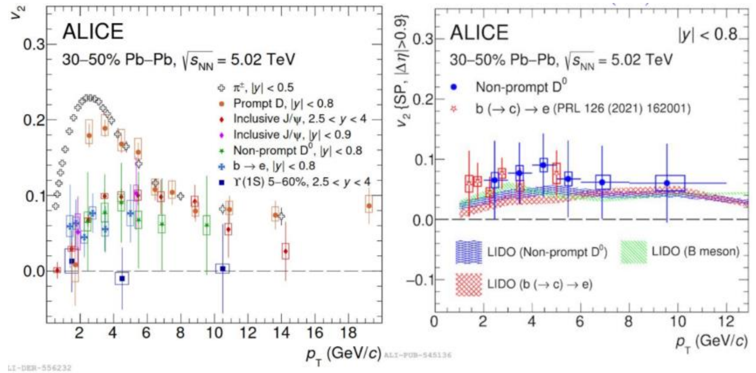
- Mass-dependent energy loss
    - Observed hierarchy of charm hadron R_{AA}: $4 < p_T < 10$ GeV/c
        - $R_{AA}(\Lambda^+_c) > R_{AA}(D^+_s) > R_{AA}(D)$ → recombination and radial flow
    - R_{AA}(non-prompt D^0) > R_{AA}(prompt D^0) → dead-cone effect
- Collectivity in heavy-ion collisions
    - Strong coupling of charm quark with QGP constituents at low p_T → charm thermalization in the medium
    - Small v_2 for beauty → weaker thermalization
    - $v_2 > 0$ for inclusive muon in high multiplicity p–Pb collisions → presence of collective-like effects in small systems also in the HF sector
- Hint of suppression at high p_T in away-side HFe-h correlation peak → hint of jet quenching

$R_{AA}(\Lambda^+_c)$, 0-10%
Phys. Lett.B 839 (2023) 137796

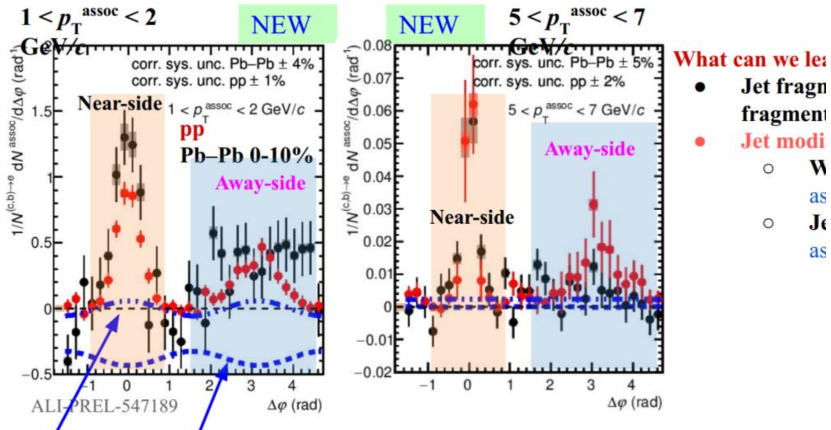


JHEP 12 (2022) 126





- v_2(non-prompt D^0) > 0 with significance of 2.7σ
- v_2(non-prompt D^0) < v_2(prompt D) > with significance of 3.2σ in the interval $2 < p_T < 8$ GeV/c



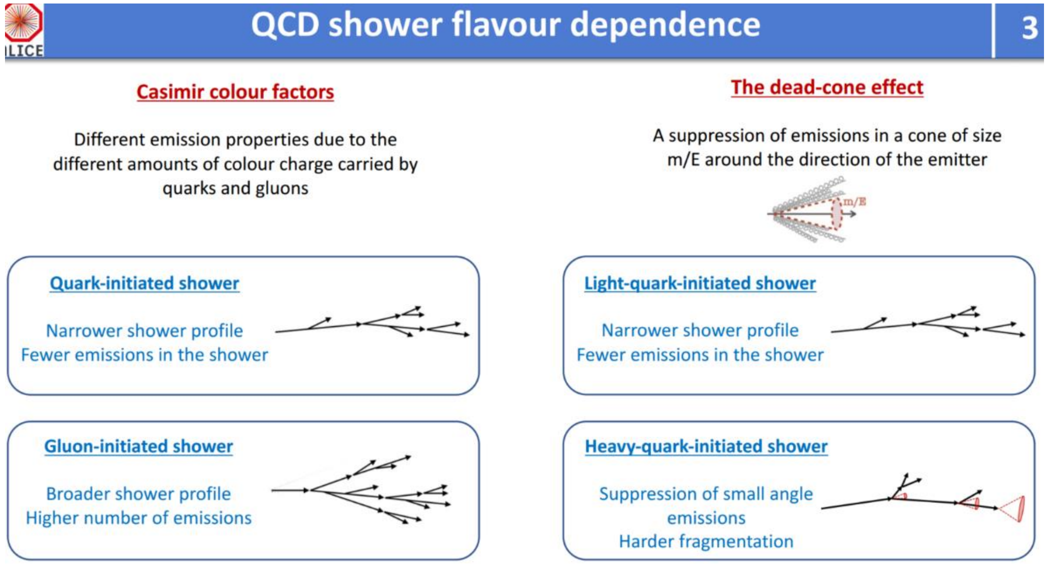
Maximum and minimum sys. of baseline → contribution from elliptic flow

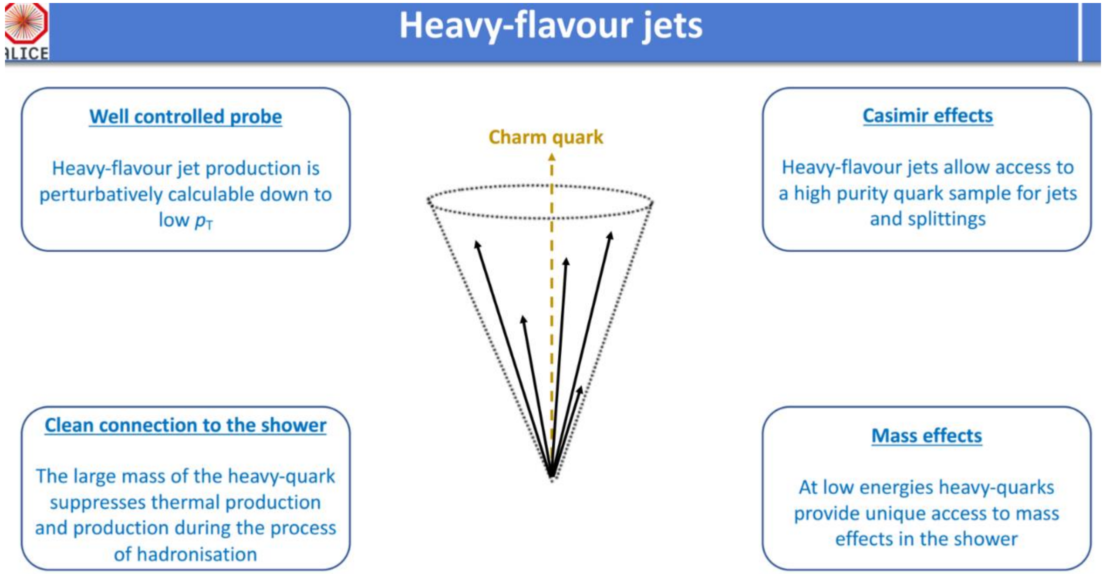
- Observed hint of suppression of yield at high p_T^{assoc} away-side peak → Jet quenching

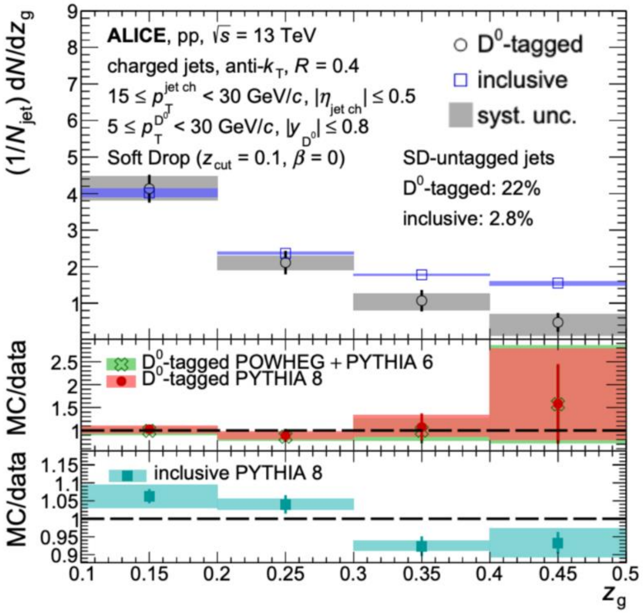
Ravindra Singh
September 5th, 2023

Heavy-flavour jet substructure for probing the flavour dependences of QCD parton showers with ALICE

Nima Zardoshti
September 5th, 2023

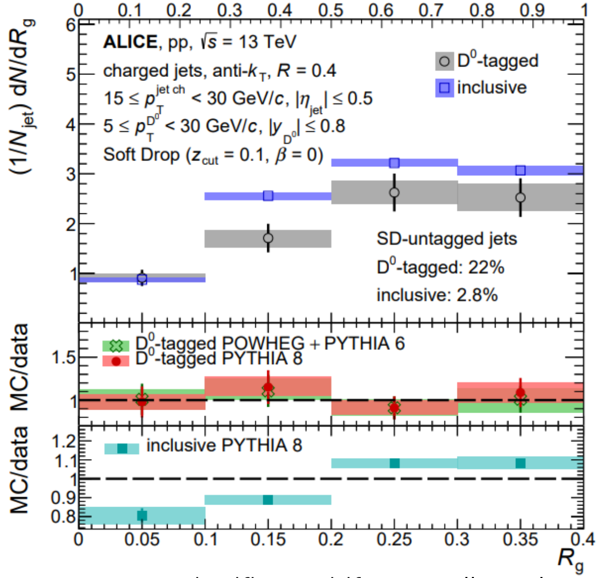


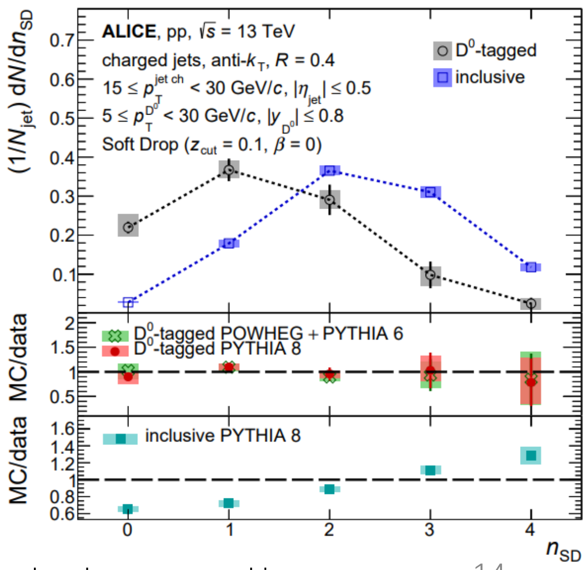




charm-tagged jets have significantly fewer symmetric splittings (large zg values), compared to inclusive jets
~ Expected mass effects in the QCD splitting function

a reduction at large-angles compared to inclusive jets
~ differences between quark and gluon fragmentation





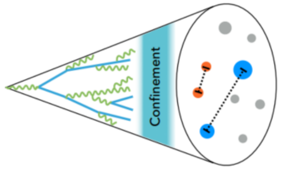
a significant shift to smaller values for the charm-tagged jets
~ the presence of a dead cone for charm quarks (satisfying the Soft Drop condition)

First energy-energy correlators measurements for inclusive and heavy-flavour tagged jets with ALICE

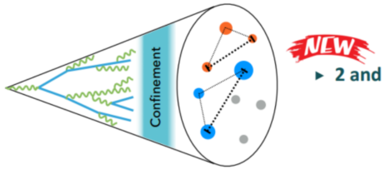
ALICE

Perturbative → Nonperturbative (NP)

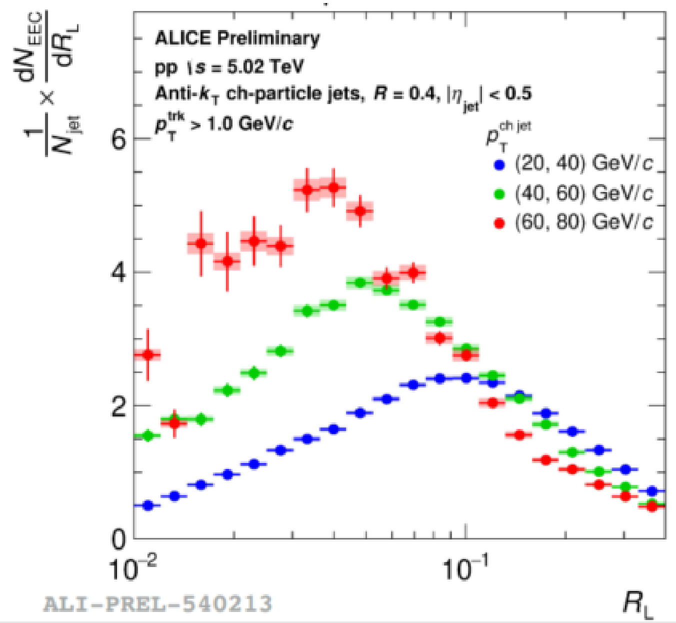
Short time scale, High energy scale — from weak to strong coupled limit — Long time scale, Low energy scale



- 2 point energy correlator results in pp at 5 TeV



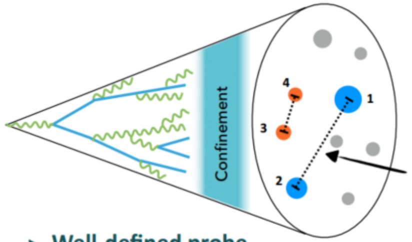
- 2 and 3 point energy correlator results in pp at 13 TeV



Different scaling behavior observed in the perturbative (large R_L) and NP region (small R_L)

Transition position shifts to lower R_L for higher jet p_T range

A new jet substructure observable: 2 point energy correlators

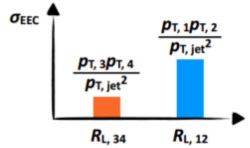


Count number of weighted pairs as function of R_L

$$R_L = \sqrt{\Delta\varphi_{ij}^2 + \Delta\eta_{ij}^2}$$

$$\frac{d\sigma_{EEC}}{dR_L} = \sum_{i,j} \int d\sigma(R'_L) \frac{p_{T,i}\, p_{T,j}}{p_{T,jet}^2} \delta(R'_L - R_{L,ij})$$

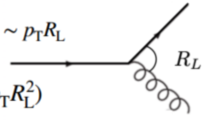
Energy weight



- Well-defined probe
  - IRC safe + pQCD calculation available: K. Lee, B. Mecaj, I. Moult (arXiv:2205.03414)
  - Soft contribution (MPI, UE) power suppressed by energy weight: no need for grooming when comparing to pQCD calculation
- Probing fixed scale with fixed R_L
  - Large ➜ small angle: perturbative ➜ NP scales
  - When the virtuality approaches $\mathcal{O}(\Lambda_{QCD})$, EEC undergo transition into confinement region

virtuality $\sim p_T R_L$

$\tau \simeq 1/(p_T R_L^2)$

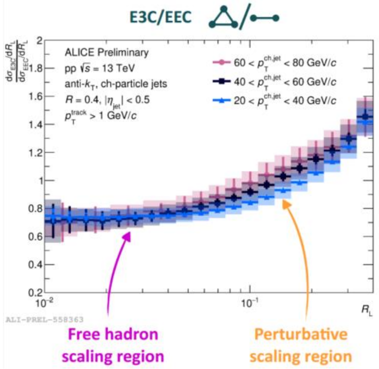


Transition $R_L \sim \mathcal{O}(\Lambda_{QCD})/p_{T,jet}$

$$\frac{d\sigma_{E3C}}{dR_L} = \sum_{i,j,k} \int d\sigma(R'_L) \frac{p_{T,i}\, p_{T,j}\, p_{T,k}}{p_{T,jet}^3} \delta(R'_L - R_{L,ijk})$$

Energy weight

E3C/EEC ratio: isolate perturbative scaling behavior



- Cancellation of NP effects and systematic uncertainties
  - Small R_L: flat shape for free hadron region
  - Large R_L: slope sensitive to α_s

E3C/EEC ratio $\propto \alpha_s(Q) ln R_L + \mathcal{O}(\alpha_s^2)$

High precision constraint on α_s from jet substructure

- Slope decrease towards higher jet p_T
  - Higher jet p_T ➜ higher Q ➜ smaller α_s ➜ smaller slope

Consistent with running of the coupling!

Wenqing Fan
September 5th, 2023