Heavy flavor production in hadronic collisions at RHIC and LHC

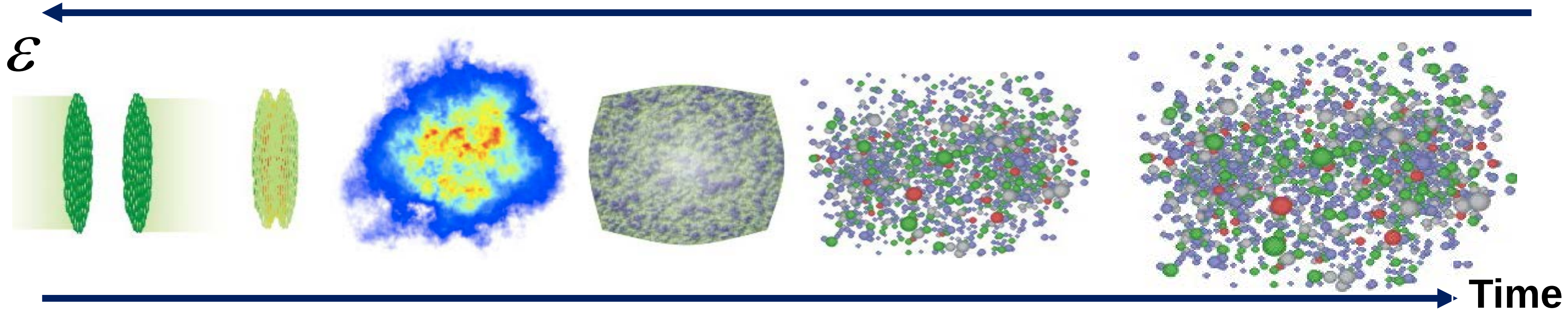
Olga Evdokimov (University of Illinois at Chicago)

Center for Frontiers in Nuclear Science
Workshop series

Opportunities with Heavy Flavor at the EIC - a CFNS Ad hoc Workshop

Introduction:

20+ years of QGP exploration on a quest to understand the strong force and confinement by creating a system of deconfined colored quarks and gluons

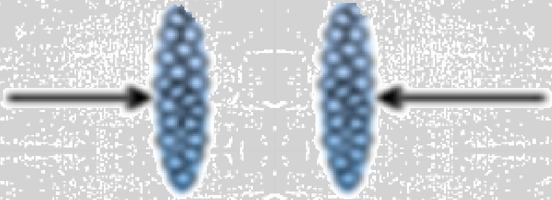


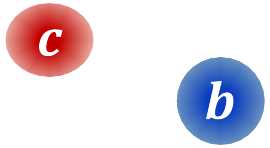
Experimental evidence of QGP formation in light hadron data:

- Initial medium temperature is well above predicted T_c
- The final system appears to be in thermal equilibrium, and is very explosive
- Medium evolution is well-described by near-ideal hydrodynamics
- Constituent quark degrees of freedom are important at hadronization

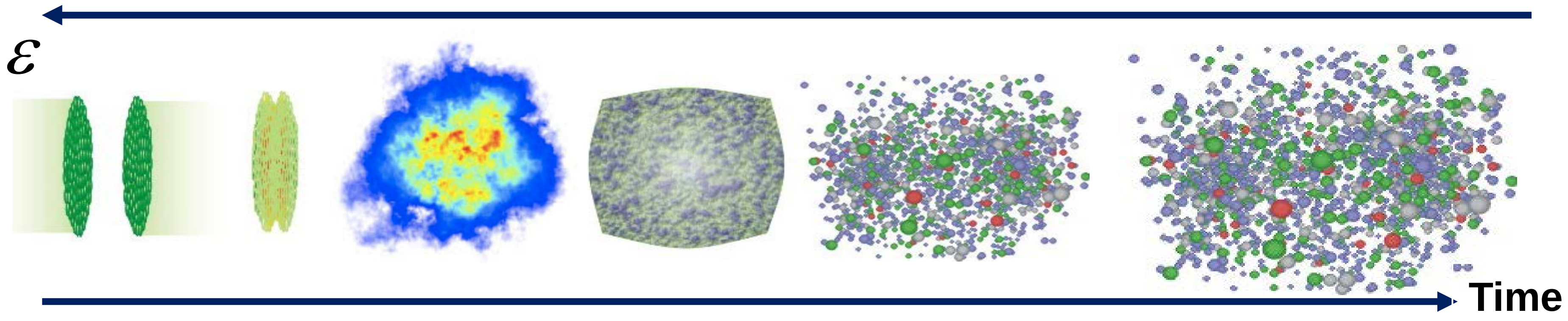
- Why go heavy?

Introduction:





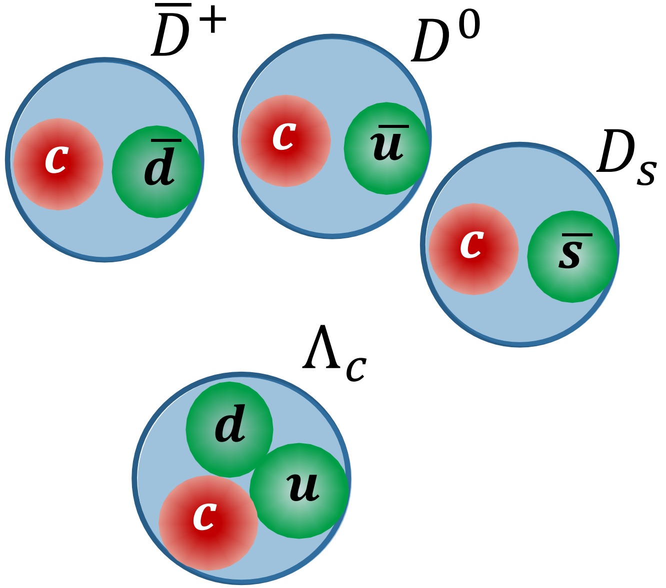
- Why go heavy?



- Produced in initial scattering ($m_c, m_b \gg T_{QGP}$); sensitive to the entire medium evolution
- Heavy ($m_c, m_b \gg \Lambda_{QCD}$) $\rightarrow$ suitable for pQCD calculations even in soft regime — Cross-sections, PDF, nPDF
- In-situ probe for energy loss $\rightarrow$ Quenching mechanisms, mass hierarchy, HF transport
- HF diffusion : Brownian motion $\rightarrow$ Diffusion coefficient
- Collective phenomena $\rightarrow$ Partonic interactions, degree of thermalization
- HF Hadronization $\rightarrow$ Mechanisms, universality

Tools of the Trade

- Experimentally, HF production and dynamics is studied through the decay products

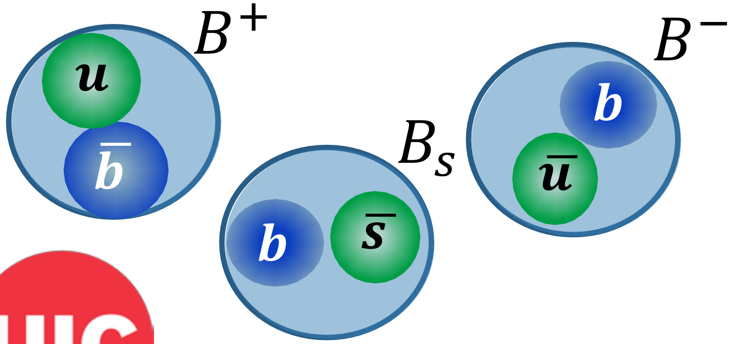


Inclusive: $D \to e + X,\ D \to \mu + X$

Exclusive: $D \to K\pi,\ \ D \to Kl\nu_l$ + displaced vertices

$D_s \to K^+K^-\pi,\ \ D_s \to \phi\pi$

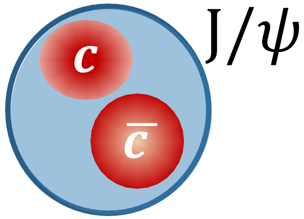
$\Lambda_c \to \pi K p$ + displaced vertex



Inclusive: $B \to D^0 + X, B \to J/\psi + X$ + displaced vertices

Exclusive: $B \to D^0\pi, B \to J/\psi K$

$B_s \to J/\psi\phi$

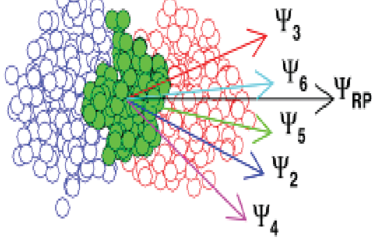


$J/\psi \to l^+l^-$

Tools of the Trade

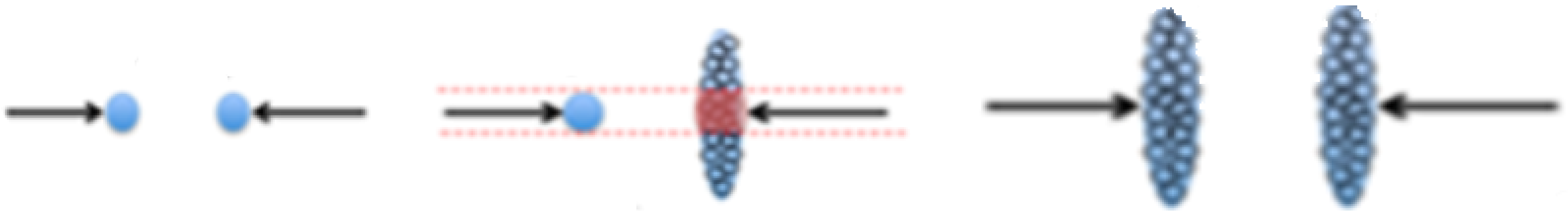
- Differential yields: $\frac{d^2\sigma}{dp_T dy}$
- Nuclear modification factors (R_{pA}, R_{AA}): $R_{AA} = \frac{\mathrm{Yield}_{AA}/\langle N_{binary}\rangle_{AA}}{\mathrm{Yield}_{pp}}$

Glauber-based picture:



$$\Psi_m^{pp} = \frac{1}{m}\tan^{-1}\left\{\frac{\sum_{i=1}^{N_{part}} r_i^m \sin(m\phi_i)}{\sum_{i=1}^{N_{part}} r_i^m \cos(m\phi_i)}\right\} - \frac{\pi}{m}$$

- Correlations (and especially, v_n): $\frac{d^3N}{p_T dp_T d\eta d\phi} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T d\eta}\left(1+\sum_{k=1}^{\infty} 2v_{n=km}(p_T,\eta)\cos\left[n(\phi-\Psi_m)\right]\right)$
- Baryon/meson and other ratios



Cross-sections, PDF, nPDF

Quenching mechanisms, mass hierarchy, HF transport

Diffusion coefficient

Initial state

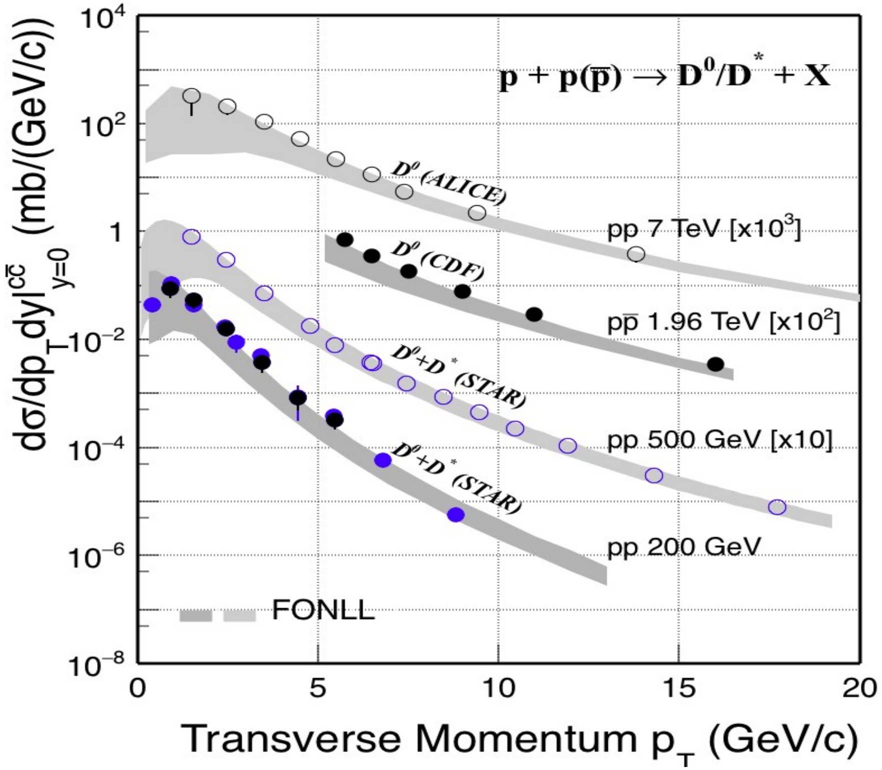
Partonic interactions, degree of thermalization

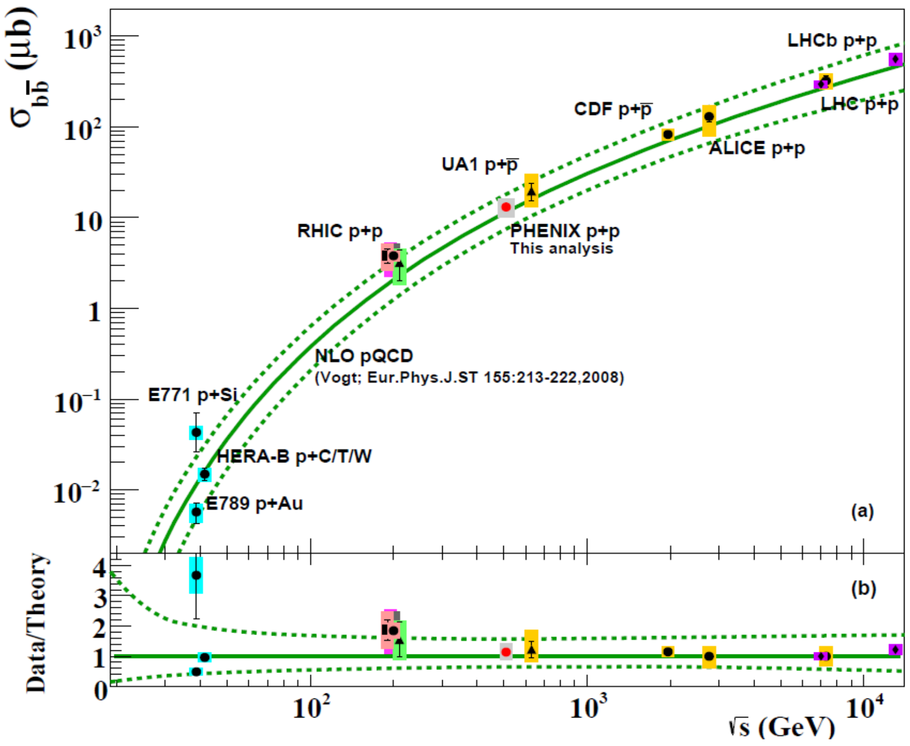
Hadronization mechanisms, universality

Heavy Flavor Production $\frac{d^2\sigma}{dp_T dy}$, $\frac{1}{N_{ev} p_T} \frac{d^2N}{dp_T dy}$

HF Production in pp

charm

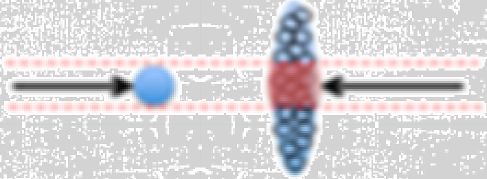


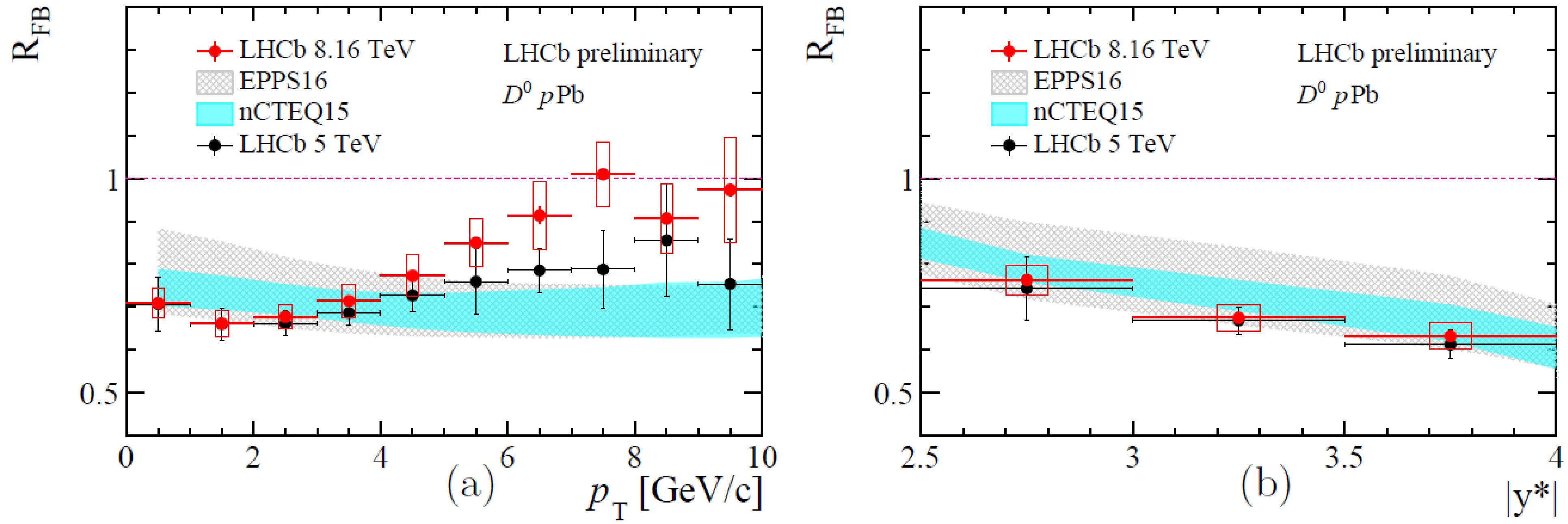


beauty

- Charm and beauty production were studied in pp collisions over vast range of $\sqrt{s}$
- Charm cross-sections are consistent with FONLL calculations (~on a high end of uncertainty bands)
- Beauty production: excitation function for $b\bar{b}$ section compared with NLO pQCD calculation

HF Production in pA



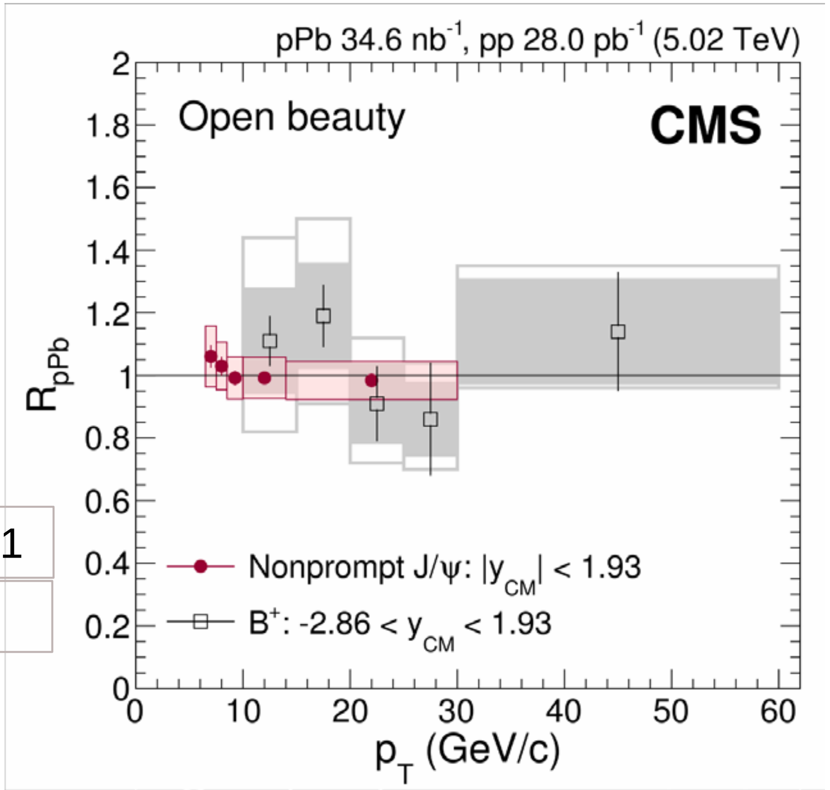


charm

LHCb-CONF-2019-004

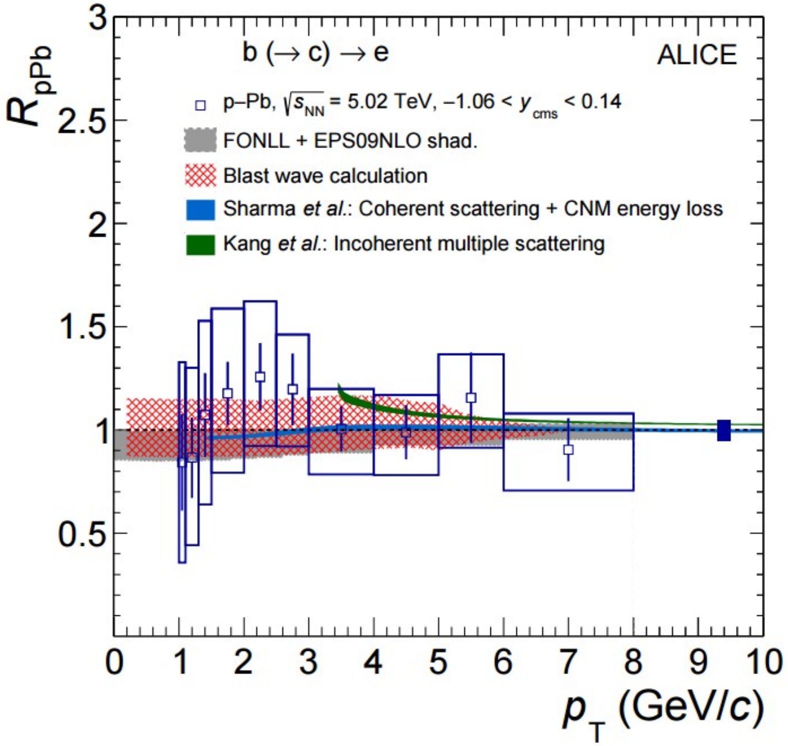
- HF production in pA: initial state studies
  - → CNM effects: nPDF constraints and universality tests, gluon saturation models, energy loss
- New pPb D^0 results: gluon nPDF constraints down to $x \sim 10^{-5}$
- Possible tensions with nPDF predictions

HF production in pA



PRL 116 (2016) 032301

EPJC 77 (2017) 269

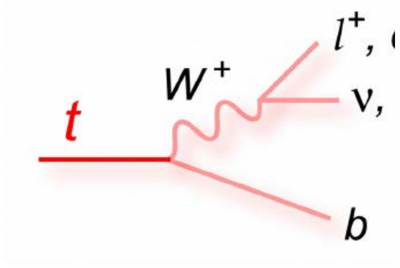


beauty

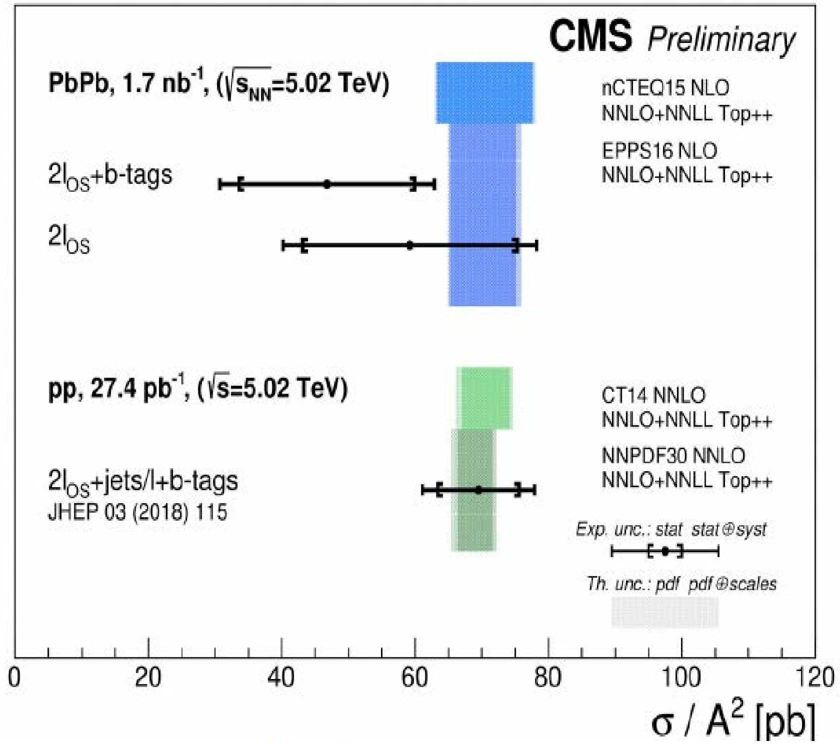
arXiv:1609.03898

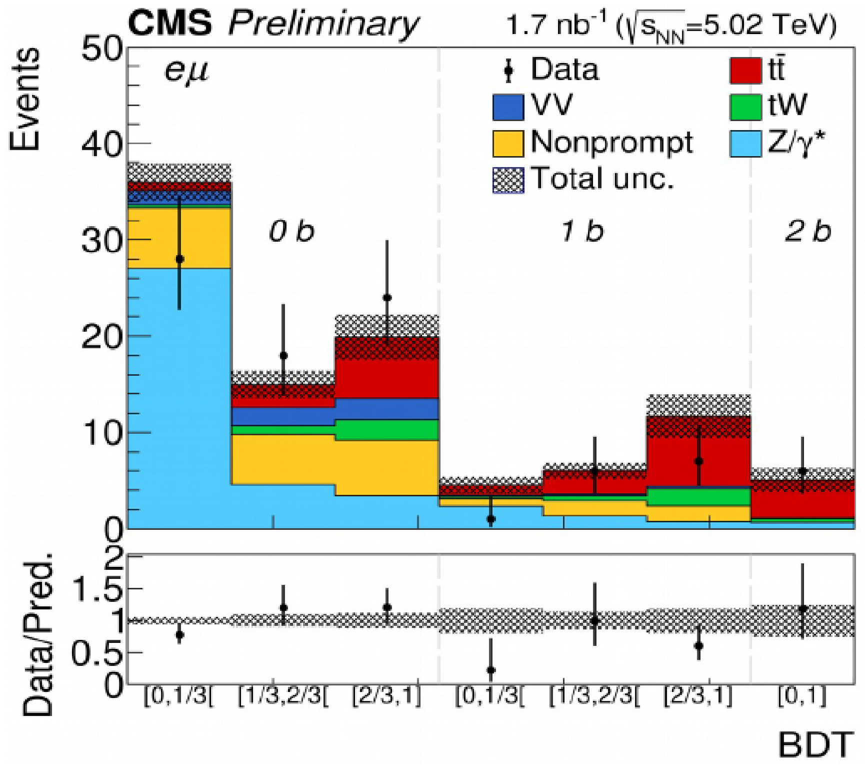
- R_{pA} for $b \to J/\psi$ and $b \to e$ shows no significant modification wrt. pp within uncertainties.
- Need higher precision data to constrain theory

Very-HF production in AA



arXiv:2006.11110





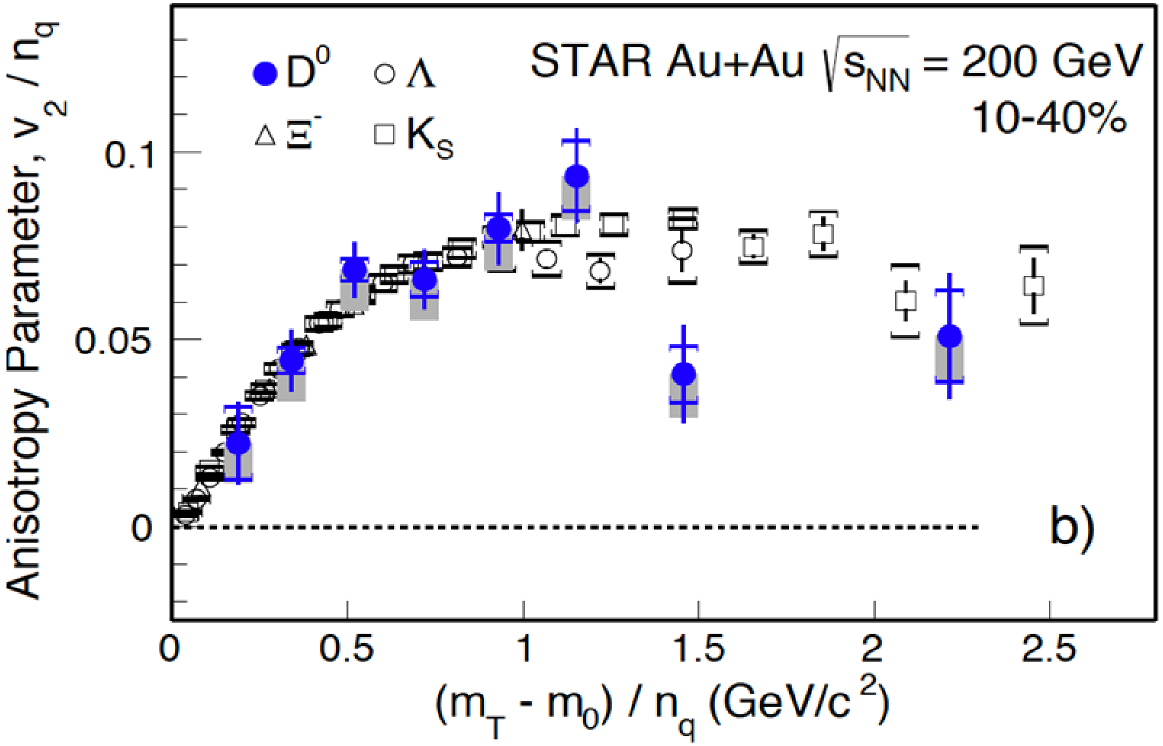
top

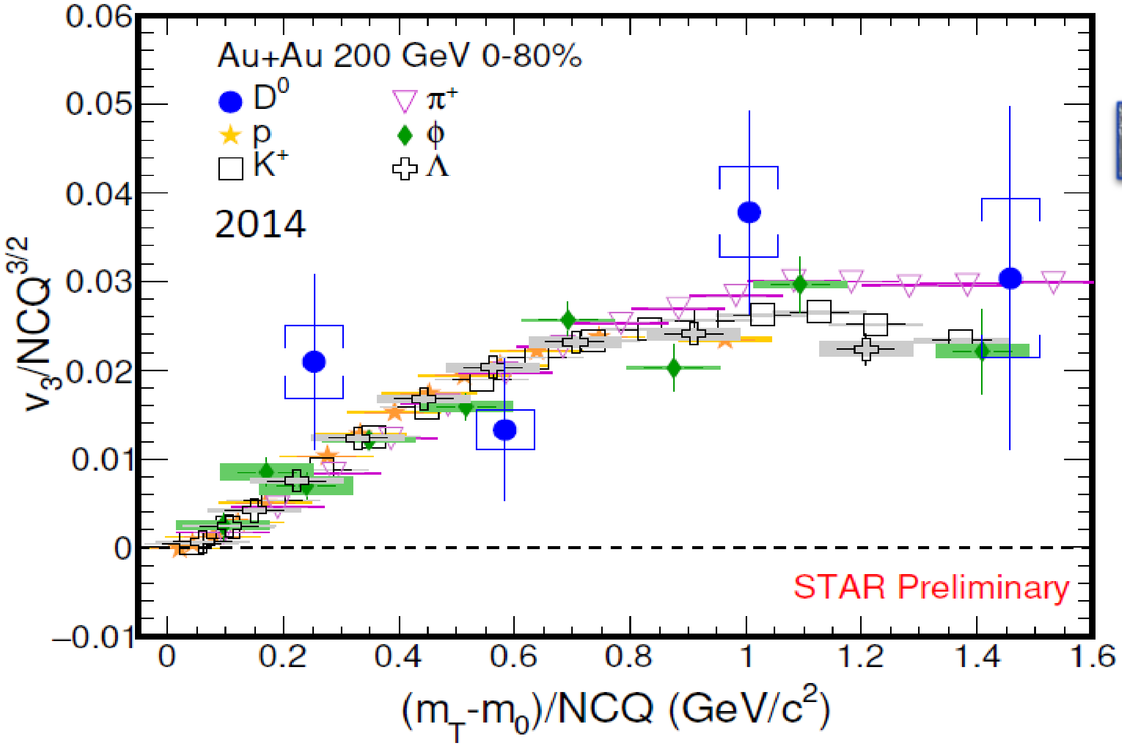
- Top quark: opportunities initial state (probes nPDF at high (x, Q)) and final state (parton energy loss)
- First experimental evidence for top quark in AA: $t\bar{t}$ cross sections via leptons+b-jets
- “Upside-down”: $t\bar{t}$ is the cleanest b-jet tagger throughout QGP evolution

HF Correlations v_n

HF Collectivity: RHIC

PRL 118 (2017) 212301



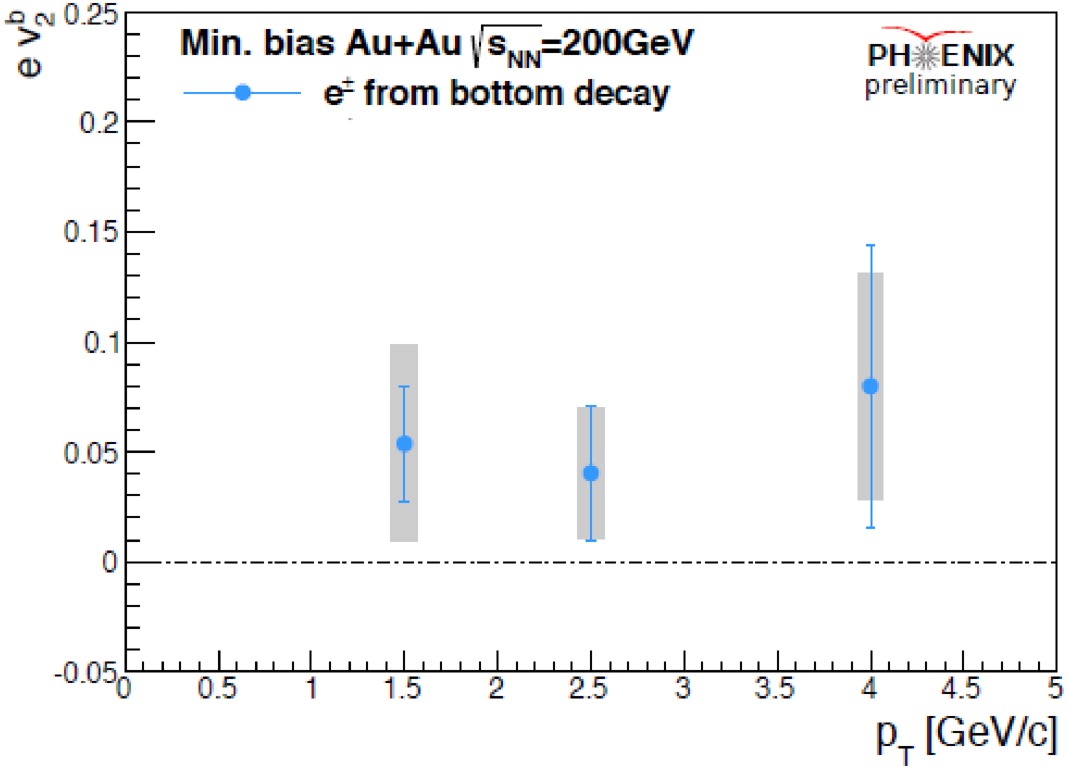


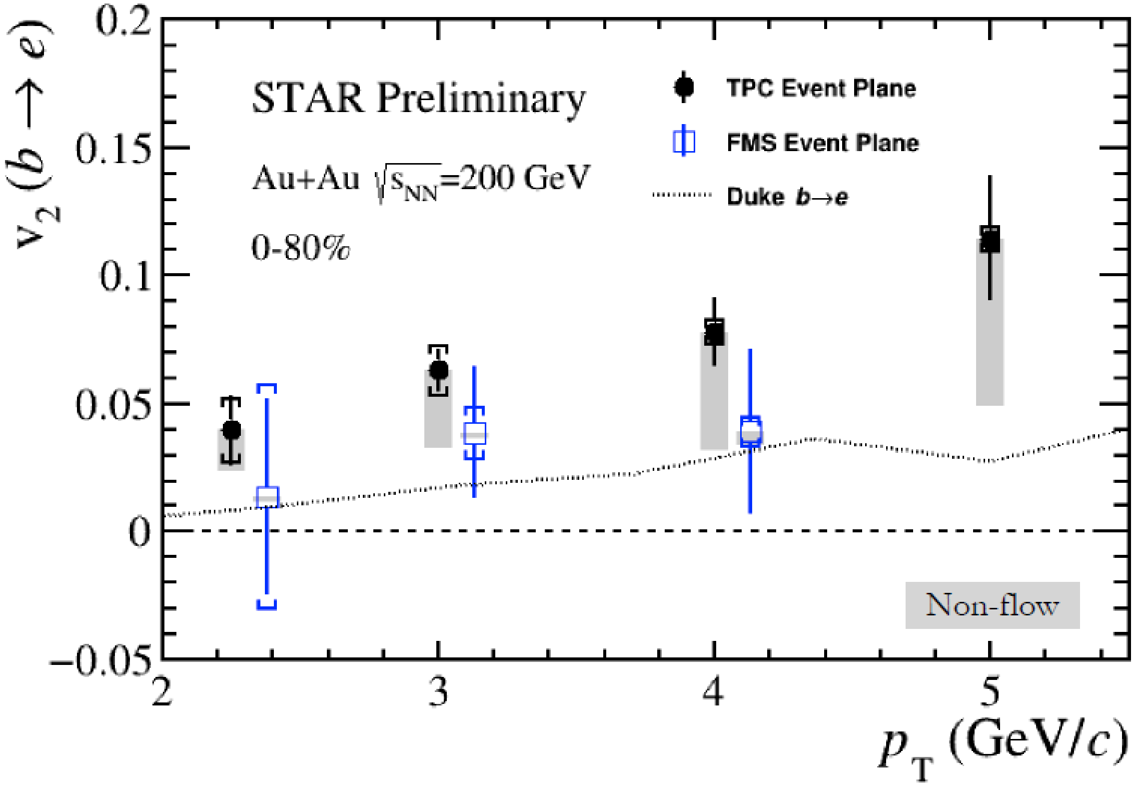
charm

- *AuAu*: significant v_2 and v_3 for D^0 mesons
- Charm v_2 follows N_{CQ} scaling trend with light hadrons

$\rightarrow$ charm collectivity and possibly thermalization

HF Collectivity: RHIC

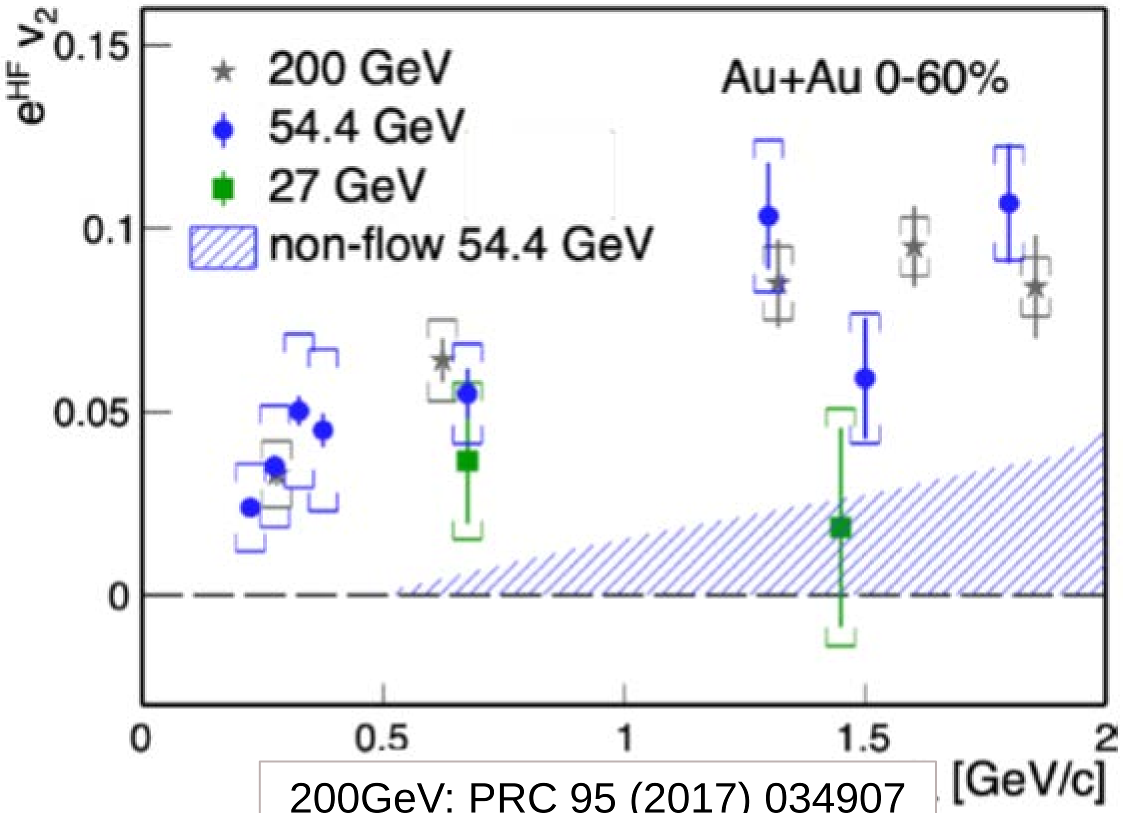




beauty

- $AuAu$: a non-zero $b \to e\ v_2$ observation
- Consistent results from PHENIX & STAR: beauty v_2 < charm v_2
- Data qualitatively consistent with non-flow model (Duke)

HF Collectivity: RHIC/BES



200GeV: PRC 95 (2017) 034907

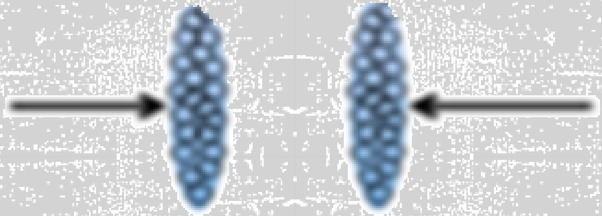
- HF collectivity: what about temperature dependence?
- RHIC BES v_2 measurements for $b + c \to e$

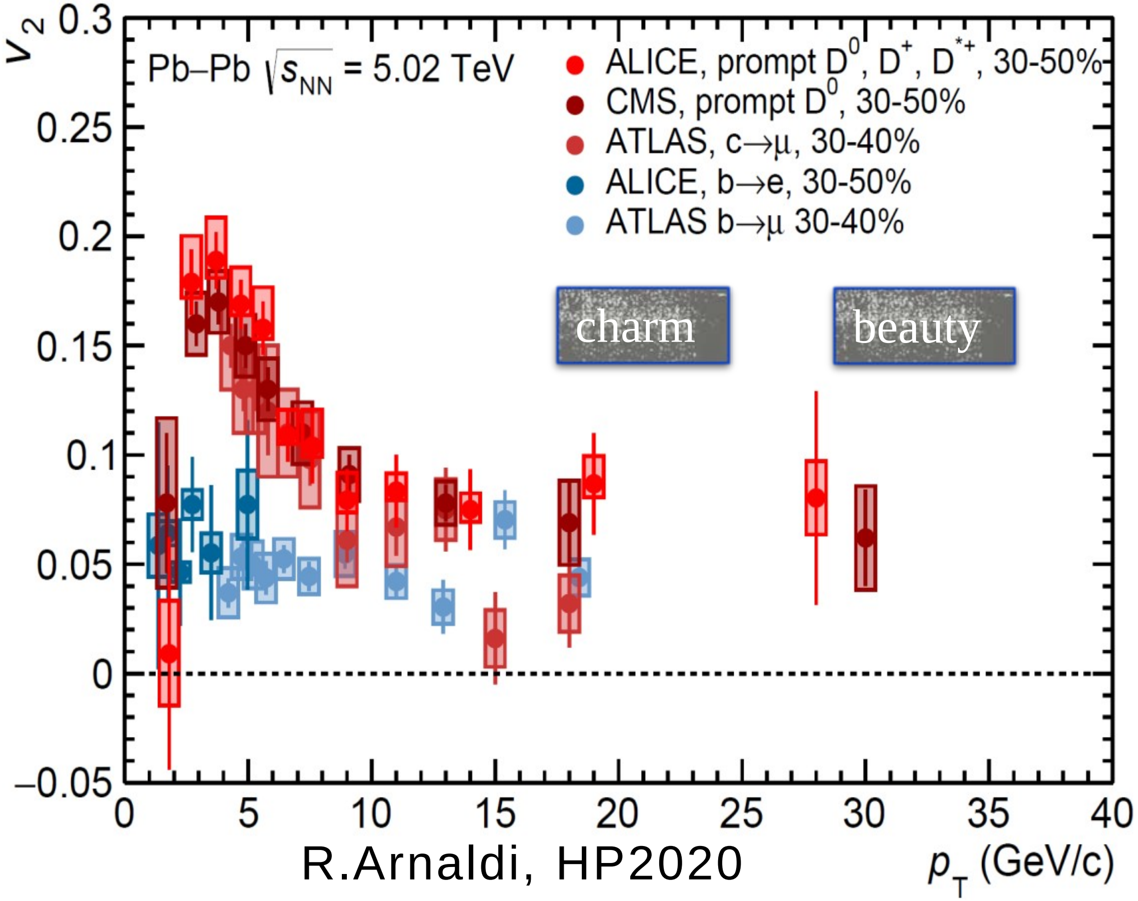
charm

Strong charm-medium interactions even at lower RHIC energies:

- HF v_2 @ 54.4 GeV ~ HF v_2 200 GeV ~ v_2 light flavors
- HF v_2 @ 27 GeV < HF v_2 @ 54.4 GeV ?

HF Collectivity: LHC





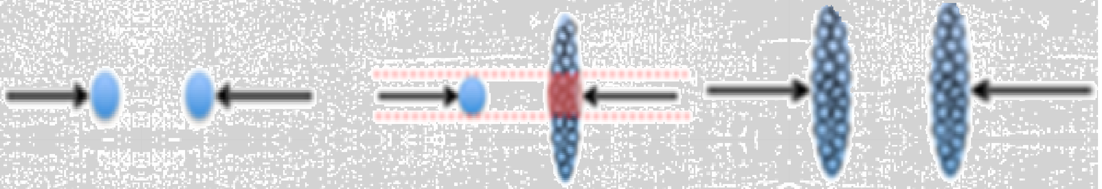
R.Arnaldi, HP2020

- LHC experiments have multiple measurements for charm and beauty v_2
- PbPb: significant v_2 for both charm and beauty, different p_T dependence
- Charm: v_2 ~ below light hadron v_2
- Beauty v_2 < charm v_2, but sizable

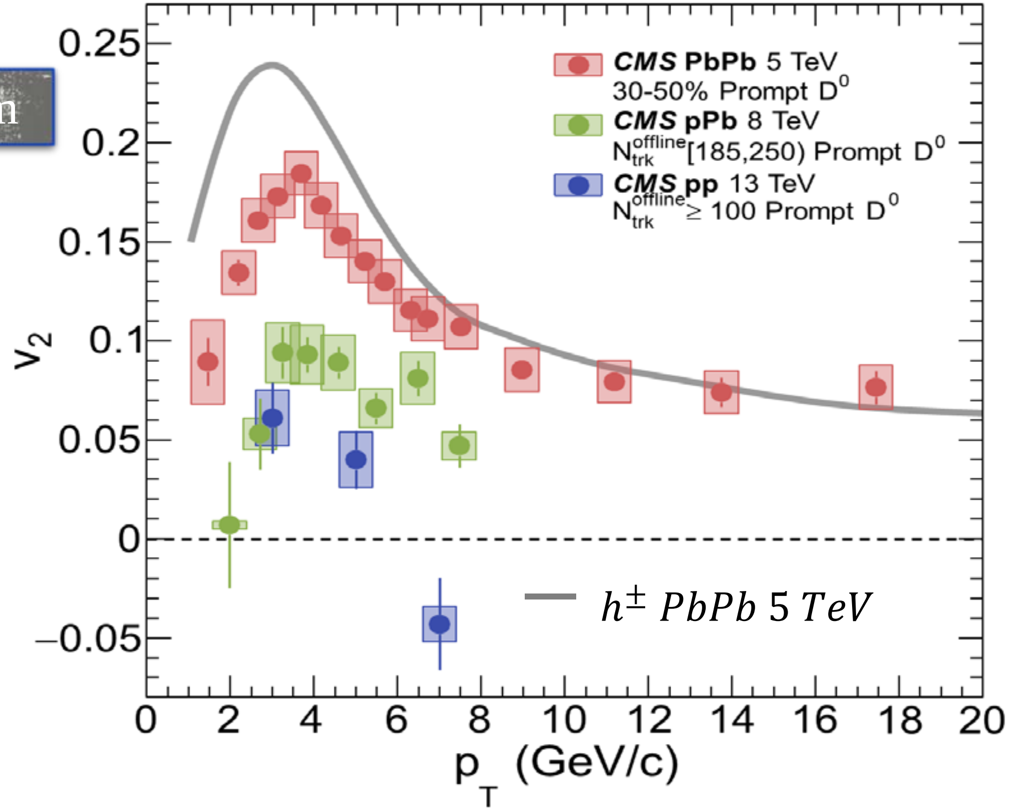
  → Indicate strong coupling to the medium
- What about p_T dependence?

  → need to disentangle energy loss, hadronization, flow, CNM...

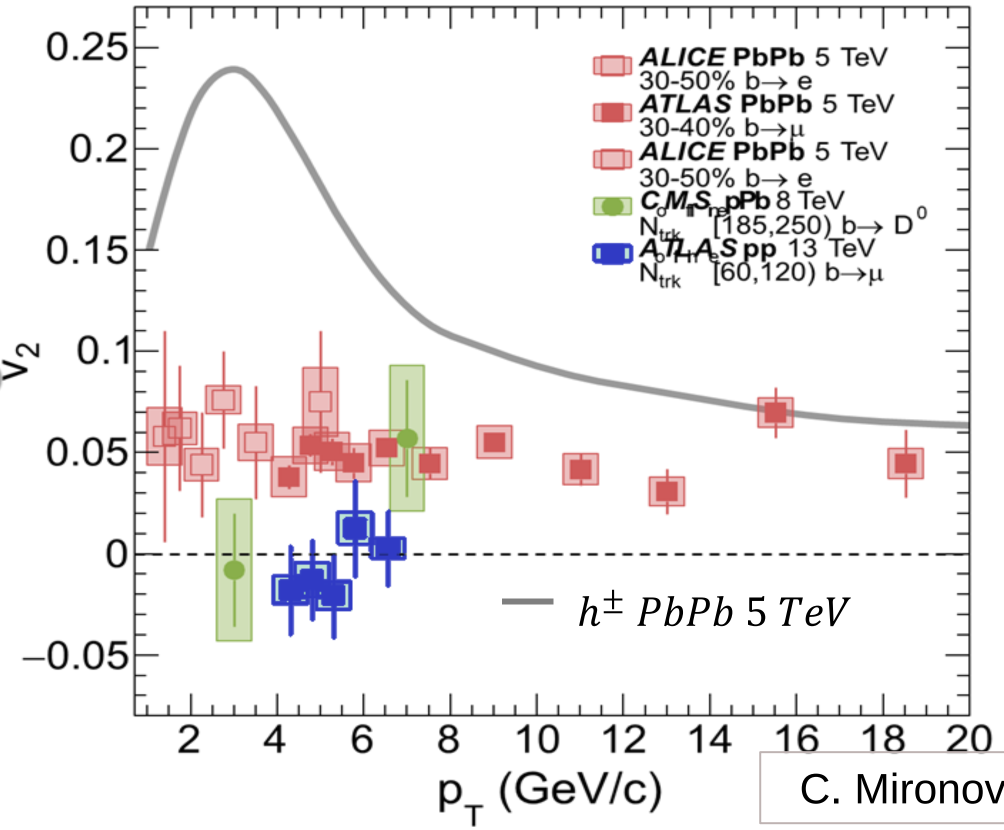
HF Collectivity: LHC



charm



PbPb
pPb
pp



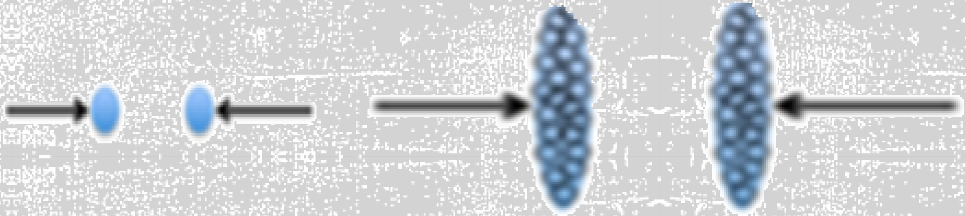
beauty

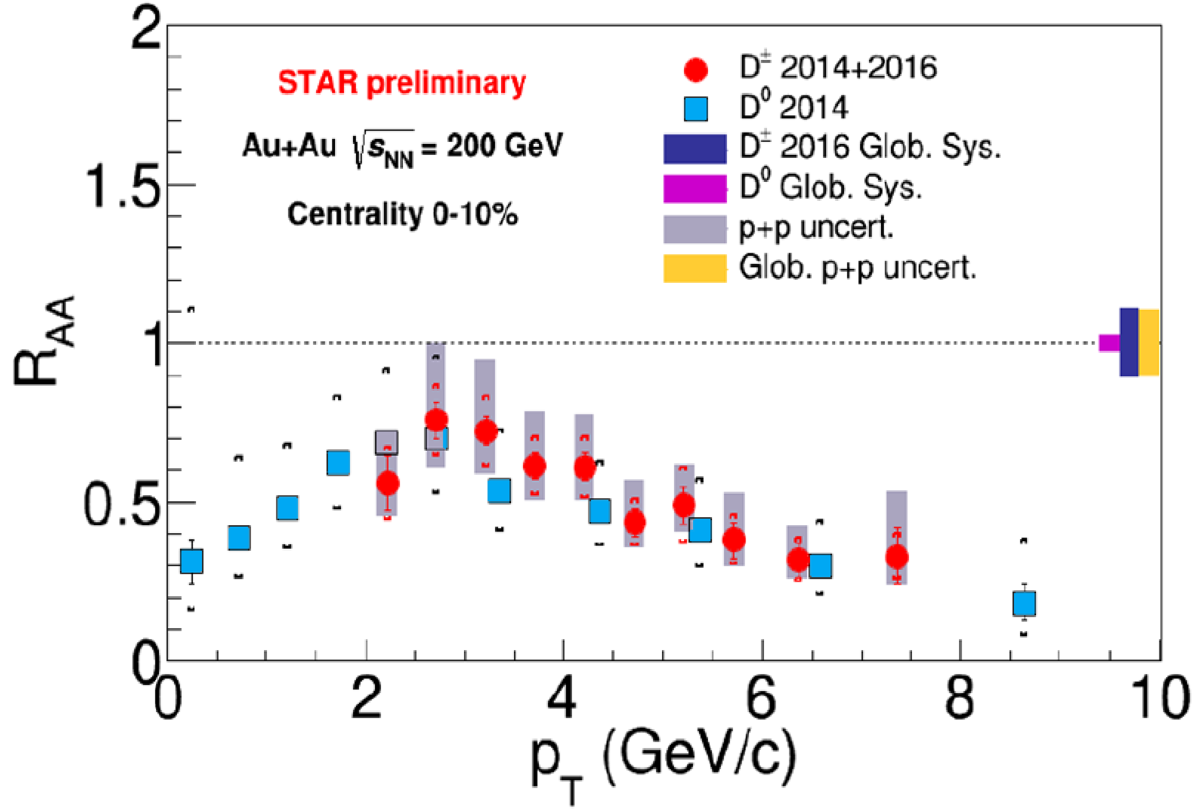
C. Mironov, HP2020

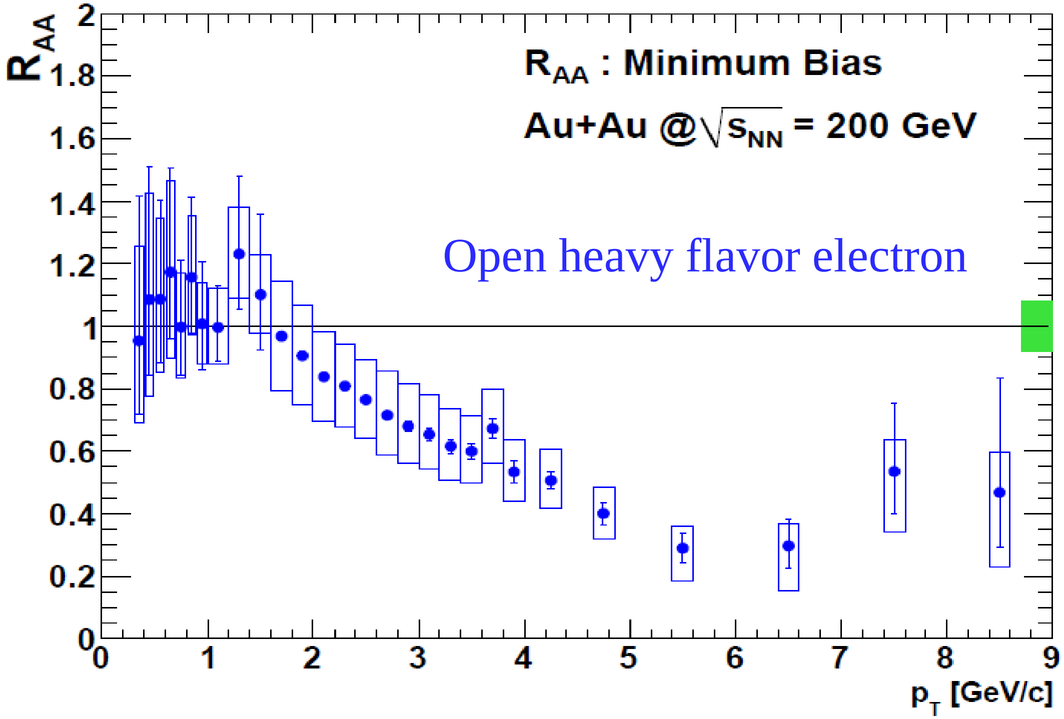
- Charm collectivity: from large systems to small $v_2(PbPb) > v_2(pPb) > v_2(pp)$
- Beauty collectivity: large systems, not small? $v_2(PbPb) > \ 0$, $v_2(pPb) \sim v_2(pp) \sim 0$
- Heavy Flavor flow in small systems: QGP? CGC?

Nuclear Modification R_{AA}

HF R_{AA} at RHIC



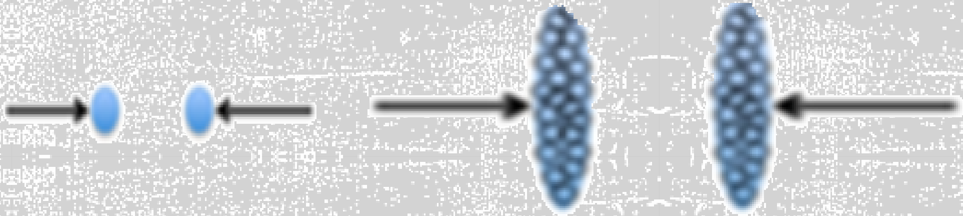


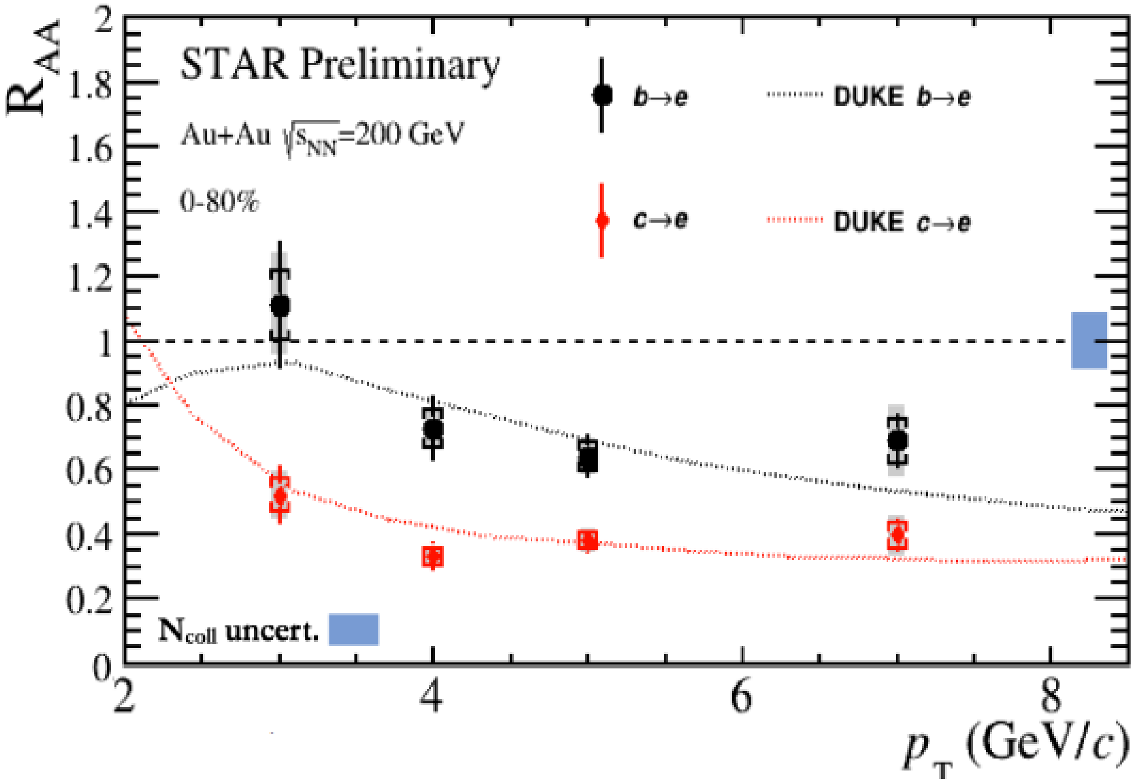


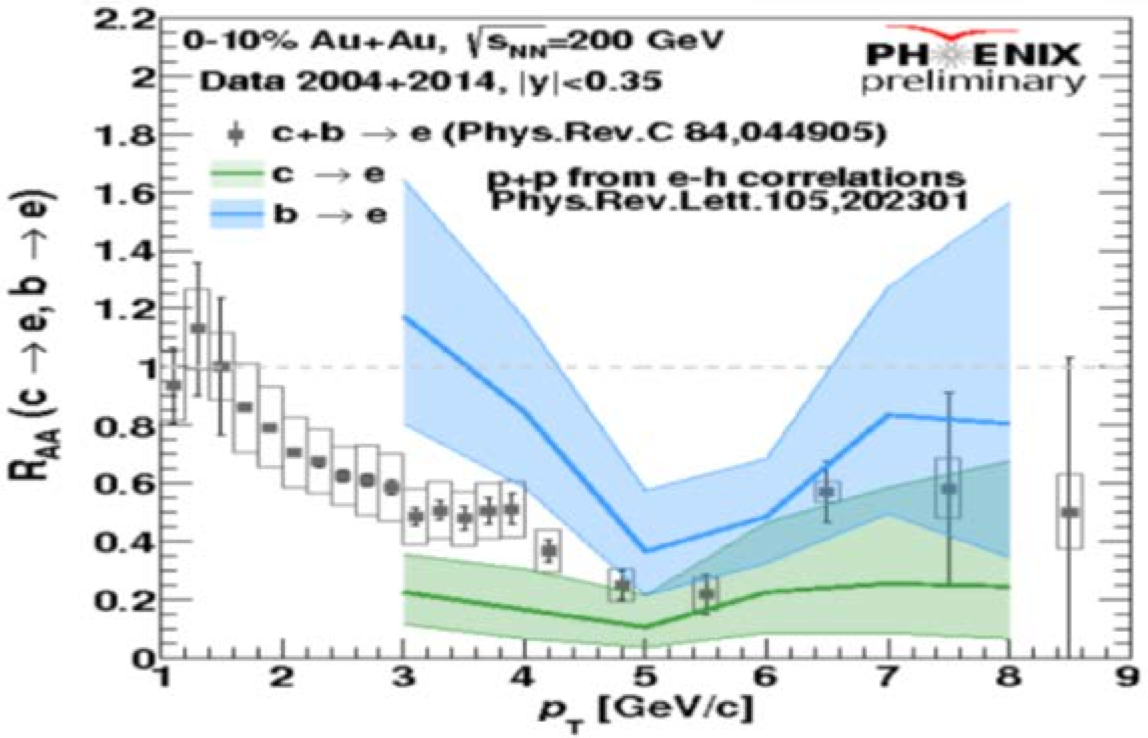
charm

- STAR $D^{\pm}, D^0$: strong suppression at high p_T
- PHENIX $c + b \to e$: strong suppression at high p_T
- Significant energy loss for charm – comparable level to light flavors

HF R_{AA} at RHIC



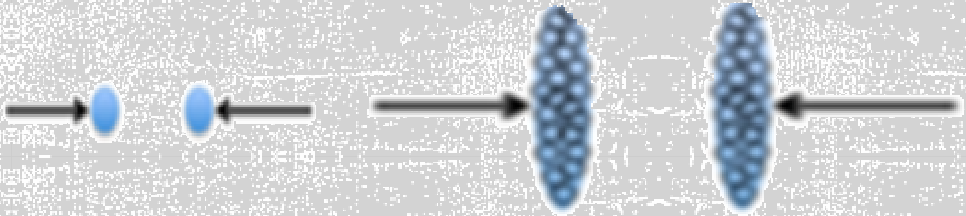




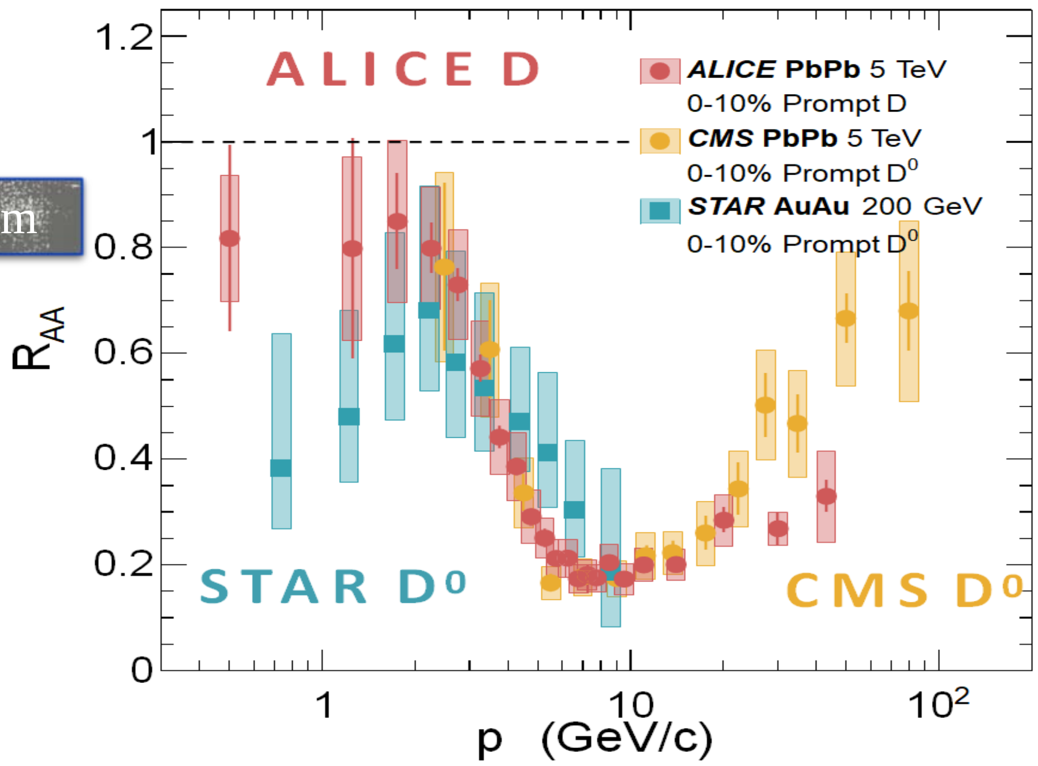
beauty

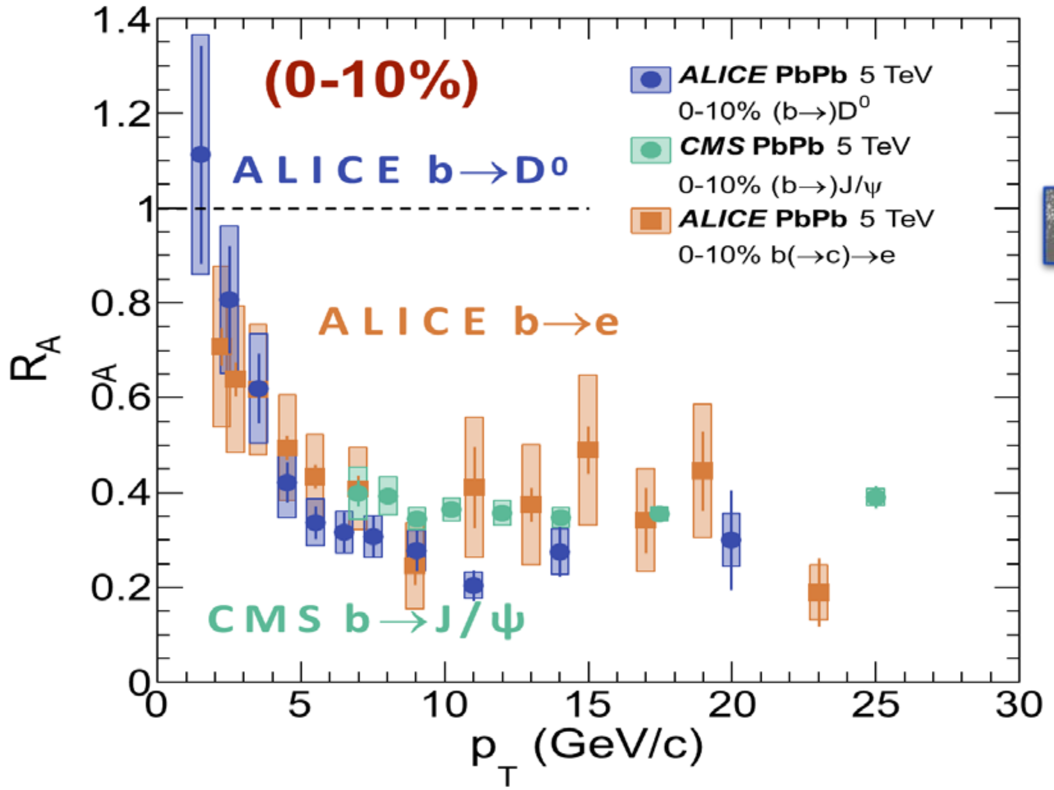
- Measurable $c \to e$ and $b \to e$ separation in the R_{AA}
- Flavor dependence of energy loss: $R_{AA}\,(b \to e) > R_{AA}\,(c \to e)$
- R_{AA} data consistent with ΔE(b) < ΔE(c) in the QGP

HF R_{AA} at LHC



charm





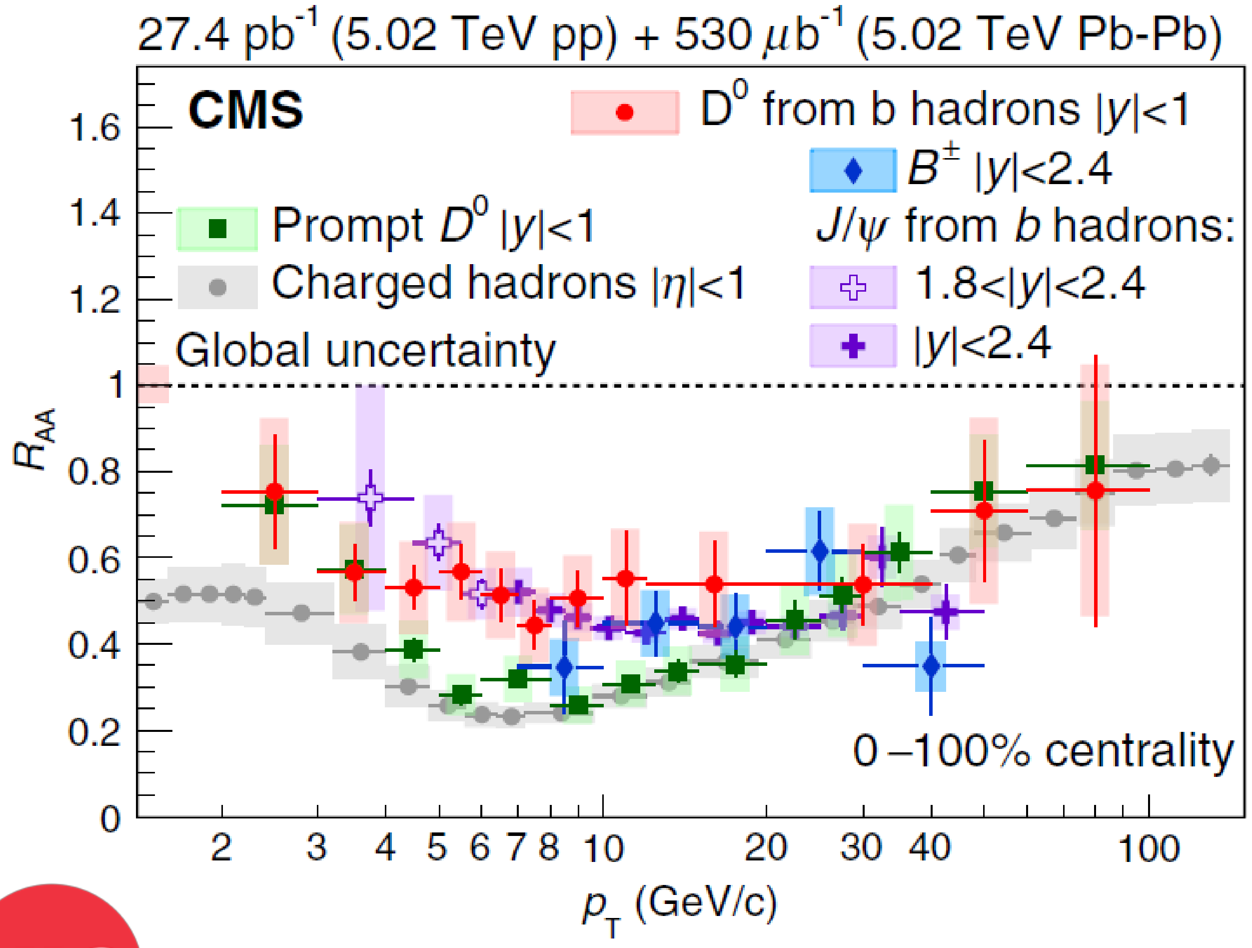
beauty

- Nuclear modification for prompt- and non-prompt D^0, non-prompt J/ψ, $b \to e$
- Mid-p_T: flavor dependence of energy loss: $R_{AA}(b) > R_{AA}(c) \sim R_{AA}(\text{light flavors})$
- Differences for charm at low p_T?

HF R_{AA} at LHC

charm beauty

PRL 123(2019)022001



- Nuclear modification for prompt- and non-prompt D^0 , non-prompt J/ψ, $B^{\pm}$
- Lower p_T : flavor dependence of energy loss

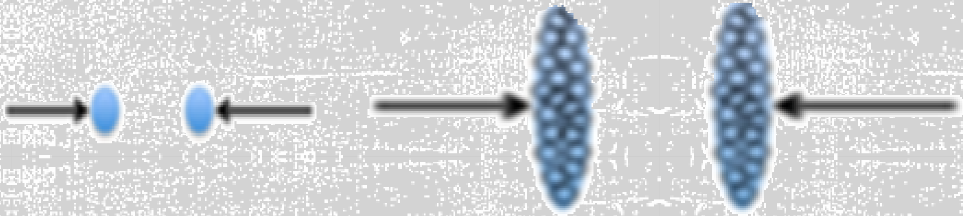
$$R_{AA}(b) > R_{AA}(c) \sim R_{AA}(\text{light flavors})$$

- High p_T : radiative energy loss dominates

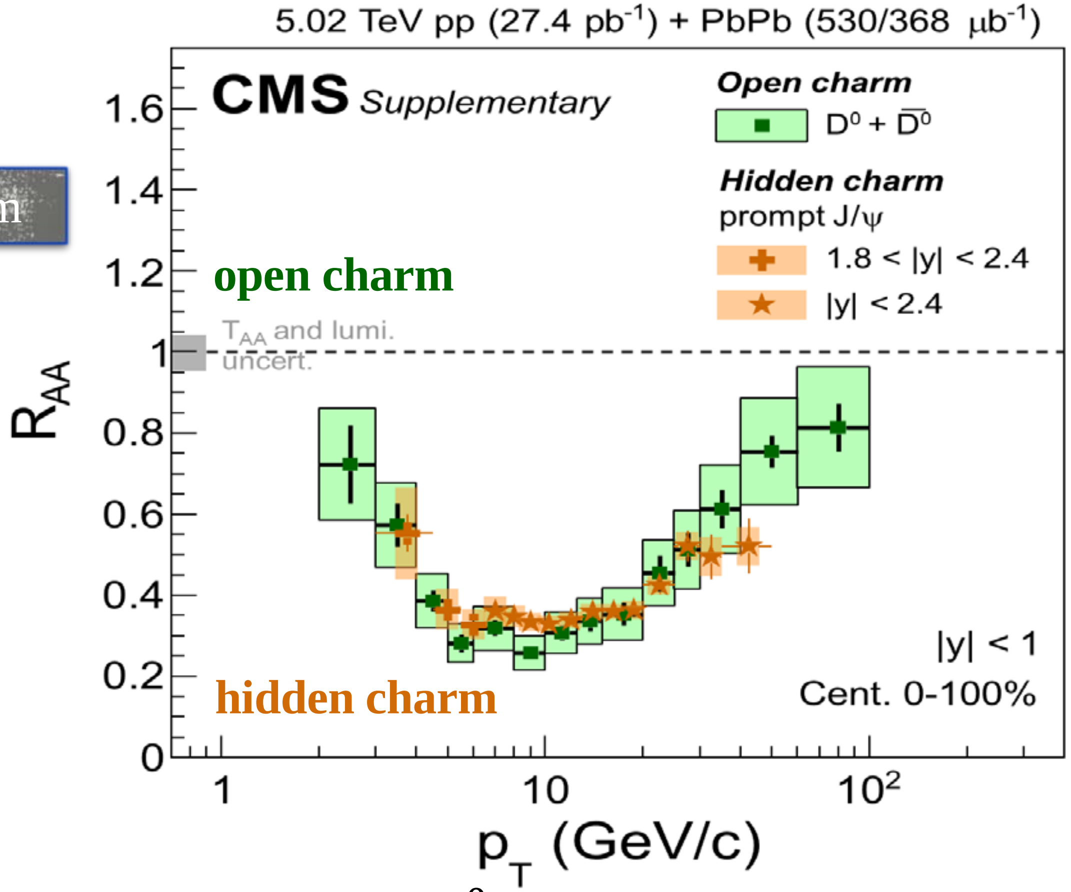
$$R_{AA}(b) \sim R_{AA}(c) \sim R_{AA}(\text{light flavors})$$

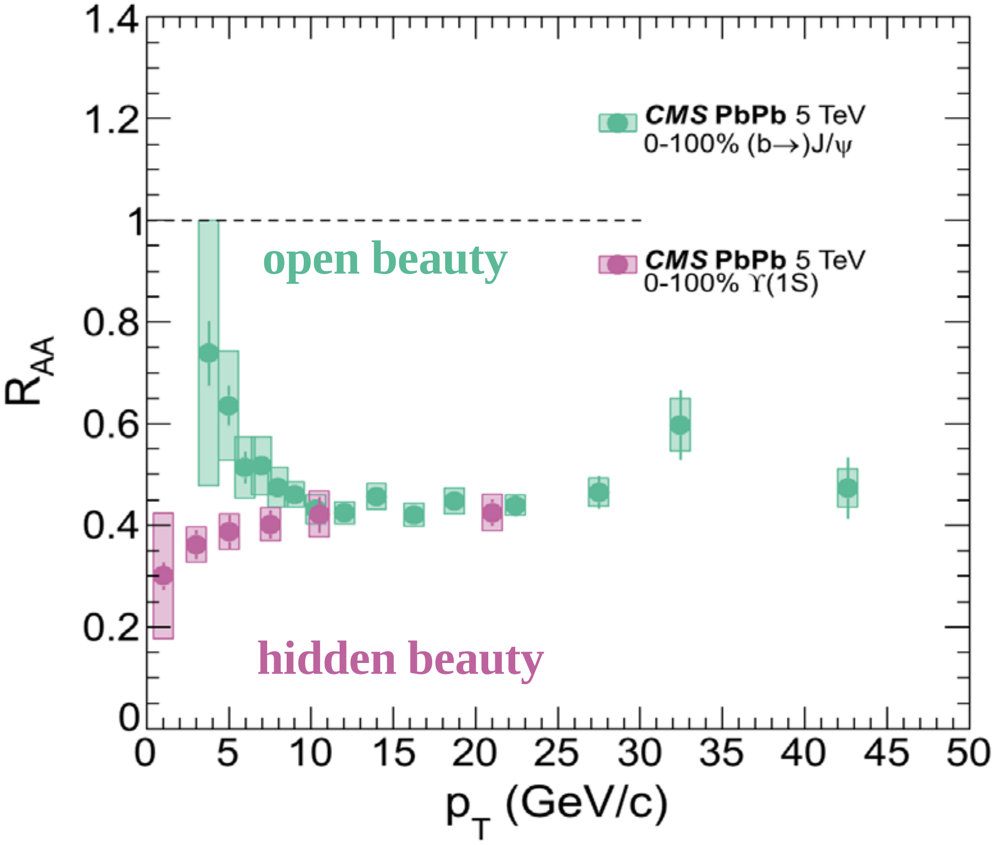
- Consistent picture with v_2 results

HF R_{AA} at LHC



charm



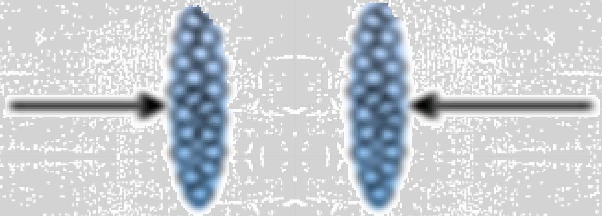


beauty

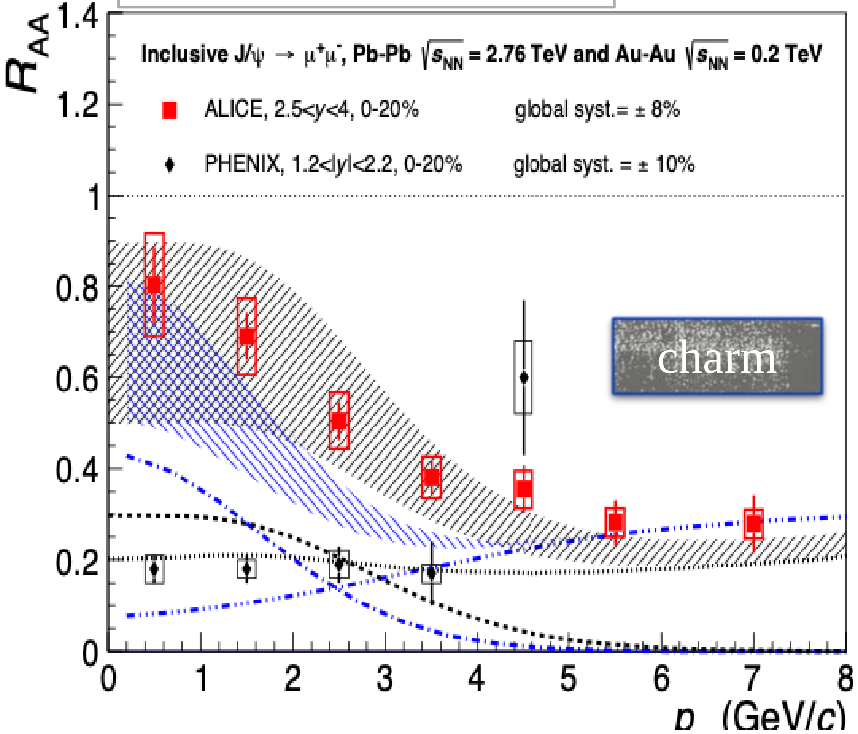
- Charm: R_{AA} for D^0 and follow the same trend for all p_T
- Beauty: R_{AA} for non-prompt J/ψ and $\Upsilon(1S)$ are similar at high p_T, split up at low

Hadronization

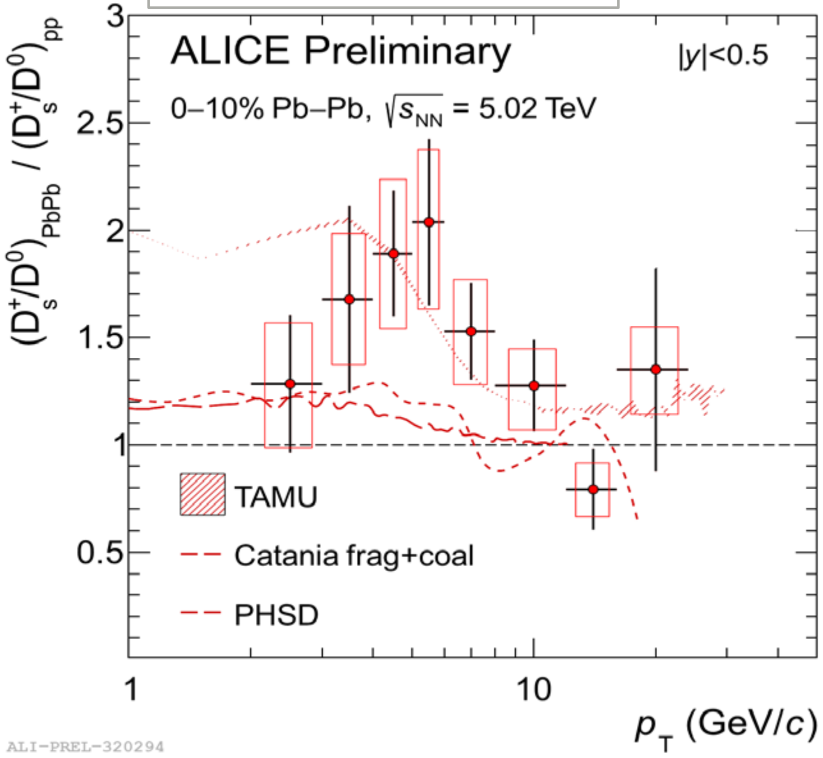
HF Hadronization AA

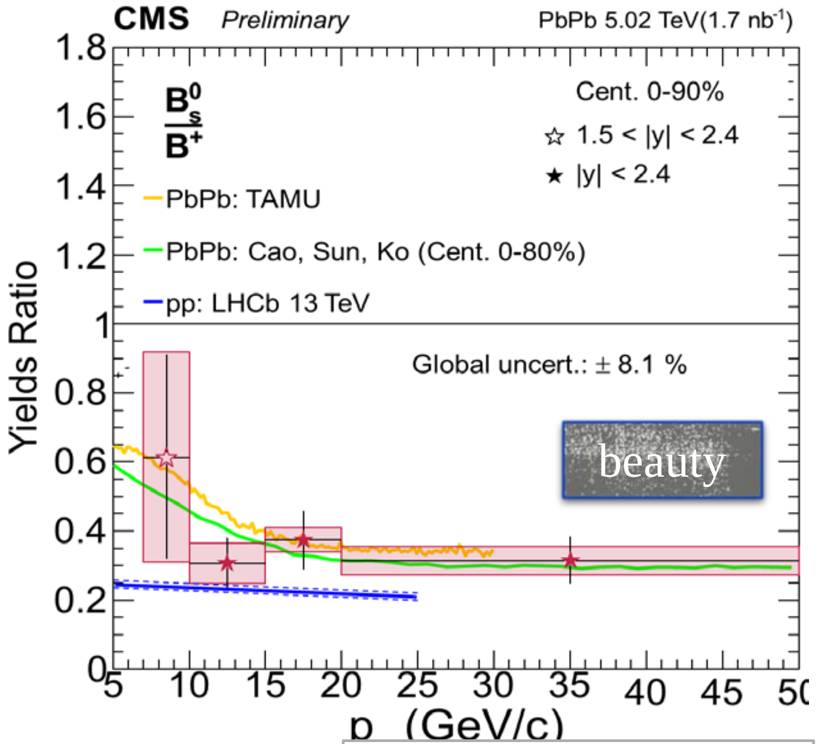


PLB 734 (2014)314



ALI-PRE-320294





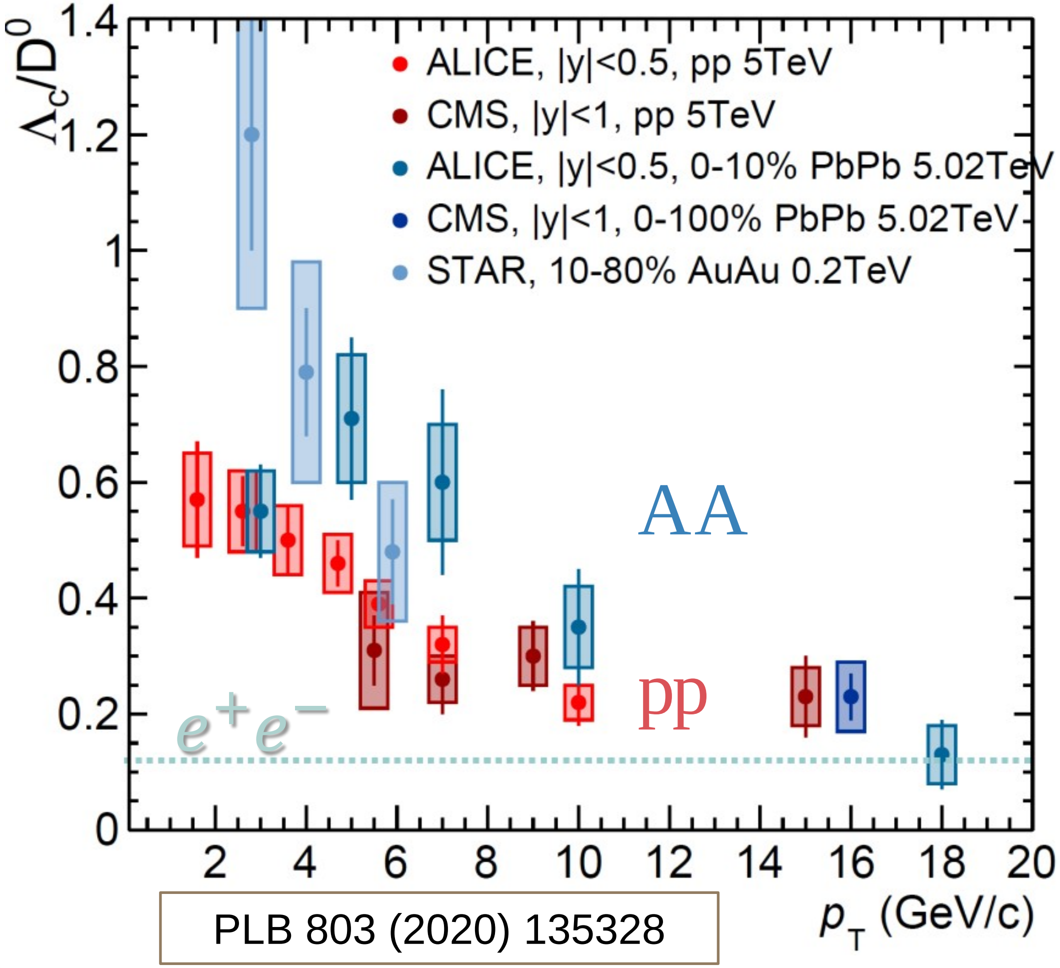
PAS-HIN-19-011

- Evidence for recombination contribution in charm-hadron sector:

  → More charm at LHC than at RHIC + recombination explains J/ψ systematics

- Strangeness enhancement + recombination would push D_s/D^0 and Bs/B+ ratios in the right direction

Charm Hadronization



PLB 803 (2020) 135328

PRL 124 (2020) 17,172301

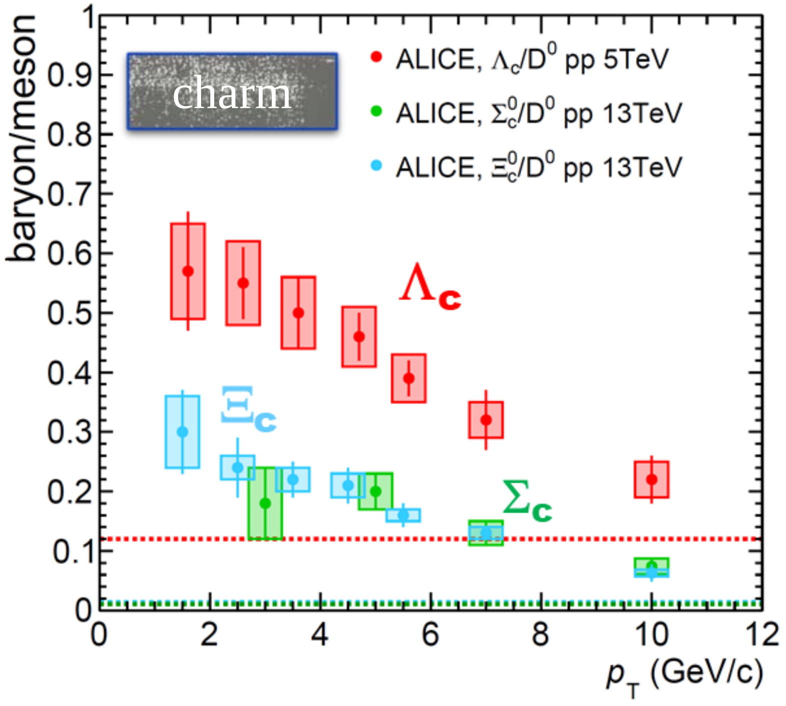
charm

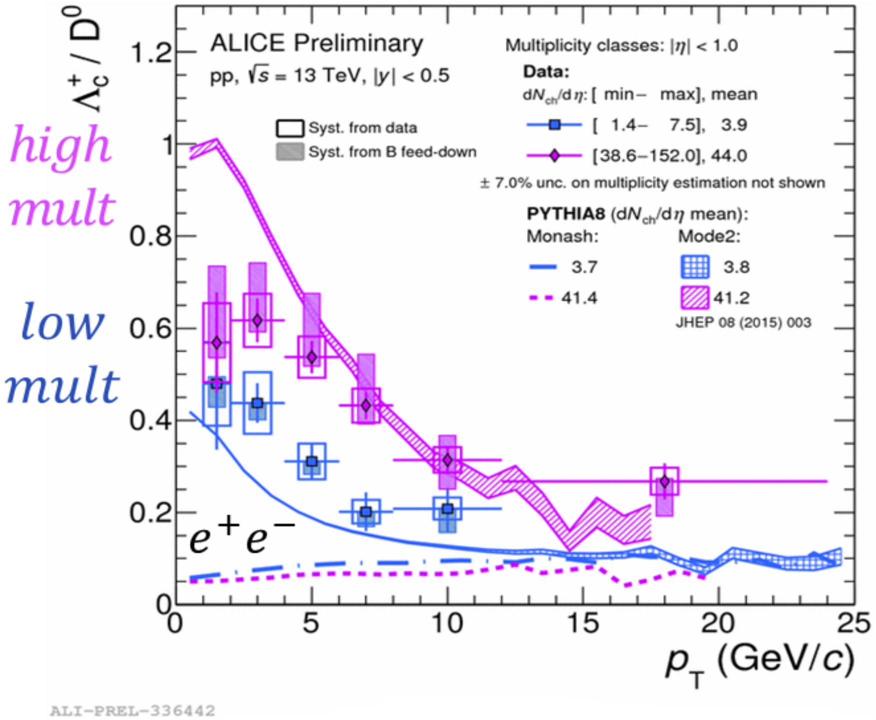
- Baryon-to-meson ratios are sensitive to hadronization
- Enhancements are seen in lights in strange sectors at RHIC
- Charm sector baryon-to-meson: Λ_c/D^0

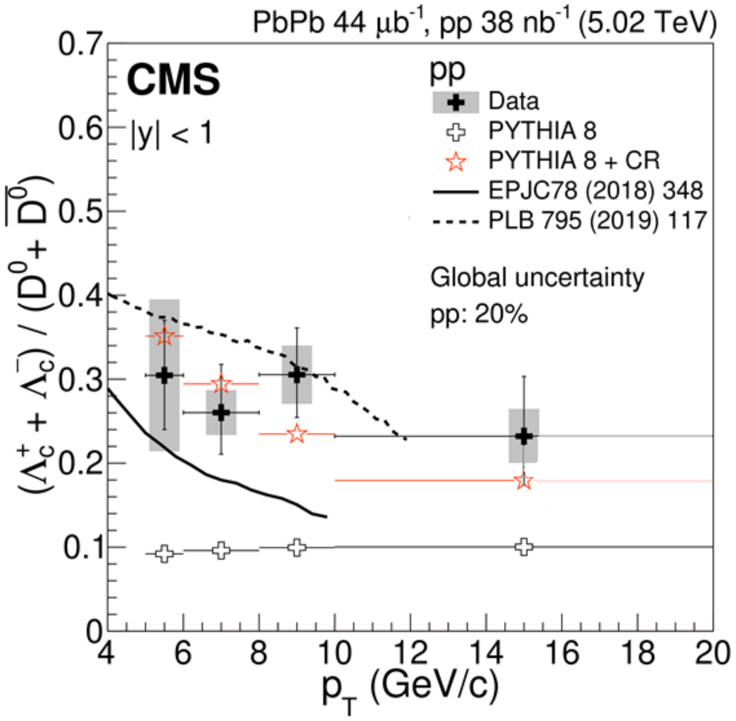
  Intermediate p_T: enhancement in AA over pp

  High p_T: similar AA to pp ratios
- Most striking feature: enhancement over e^+e^-

Charm Hadronization pp







- Recent heavy charmed baryon measurements in pp: all over the e^+e^-: factor of 5 for Λ_c, 20 for Ξ_c, 15 for Σ_c

  → contributions to Λ_c enhancement from higher mass feed-downs

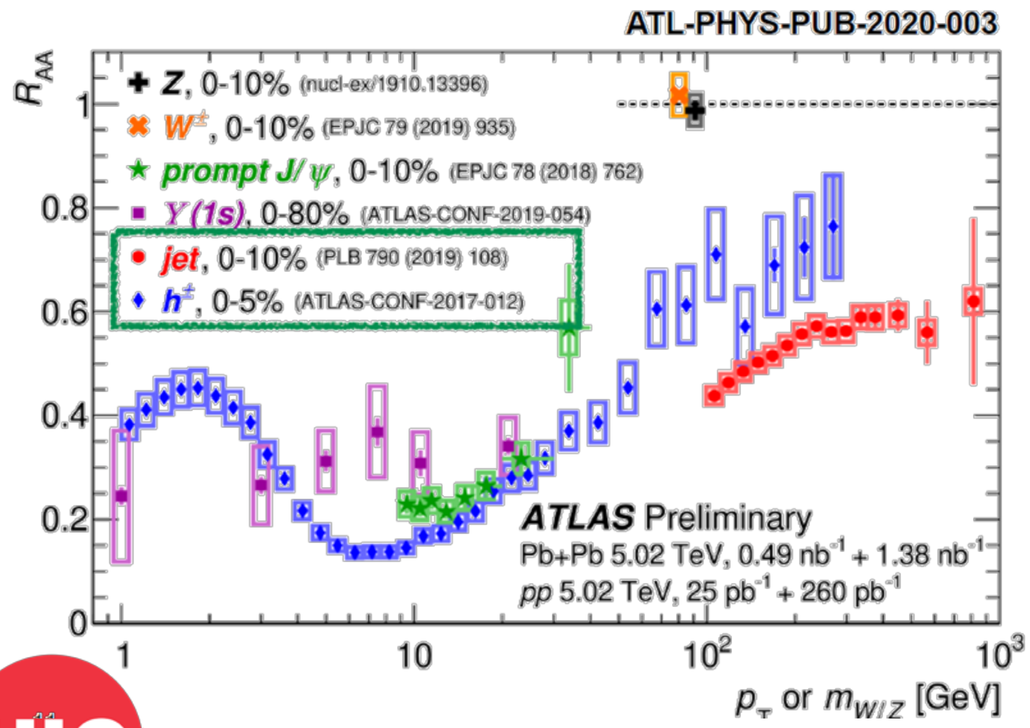
- Enhancement in pp increases from low to high multiplicity

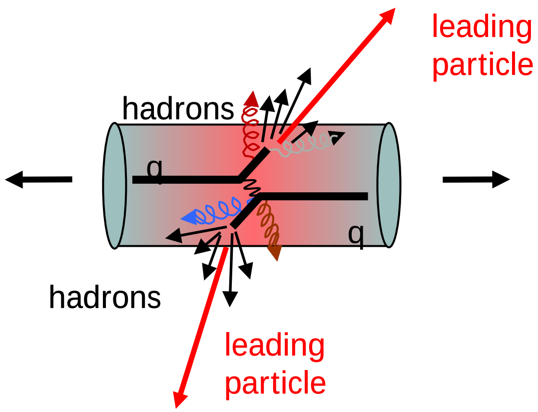
HF in Jets

HF in Jets

What happens if partons traverse a high energy density colored medium?

- Jet-medium interactions
- Flavor/color-charge dependence of parton-medium coupling
- In-medium fragmentation/ hadronization



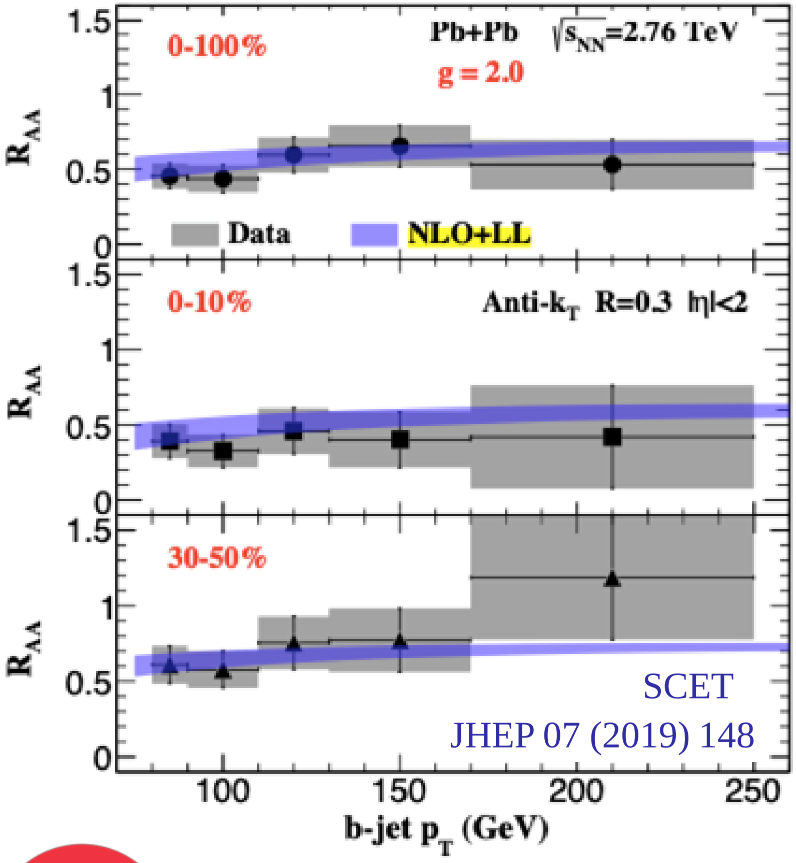


Jet quenching evident in strong suppression of high p_T hadrons…

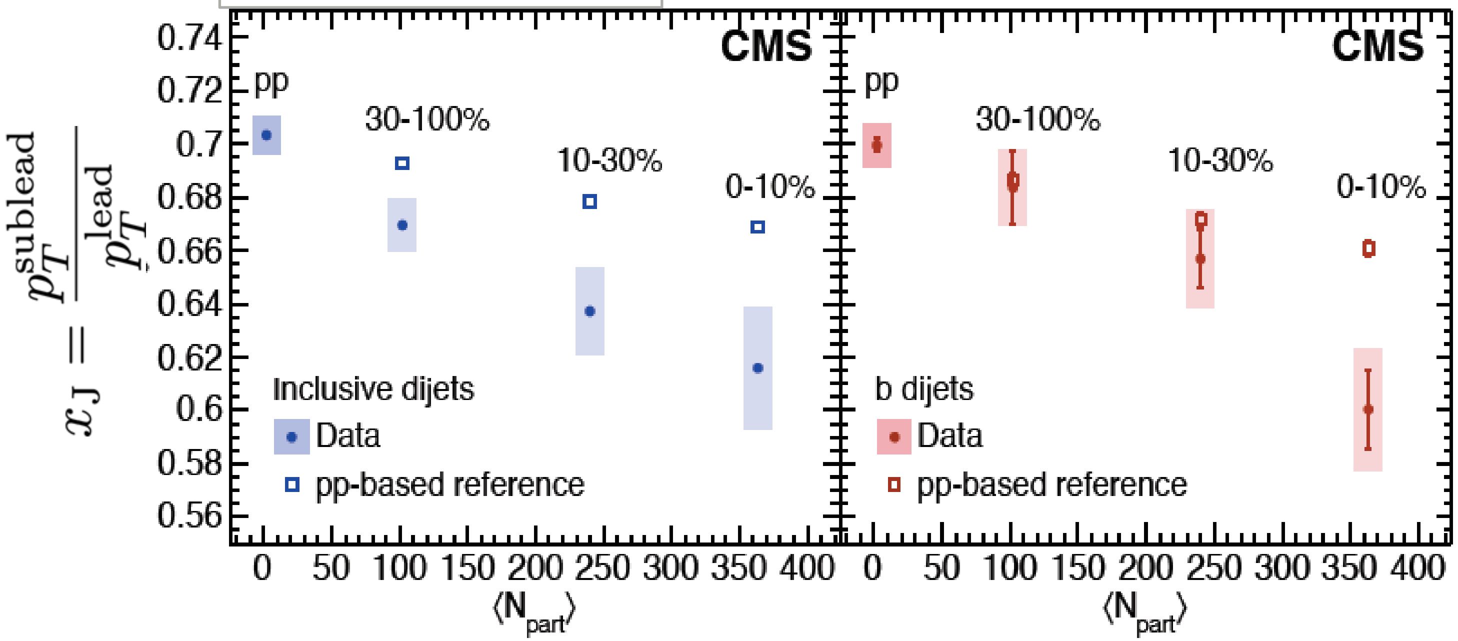
- …of all sorts and flavors
- Colorless probes pin down (otherwise model-dependent) N_{bin}

Quenching in b-jets

beauty

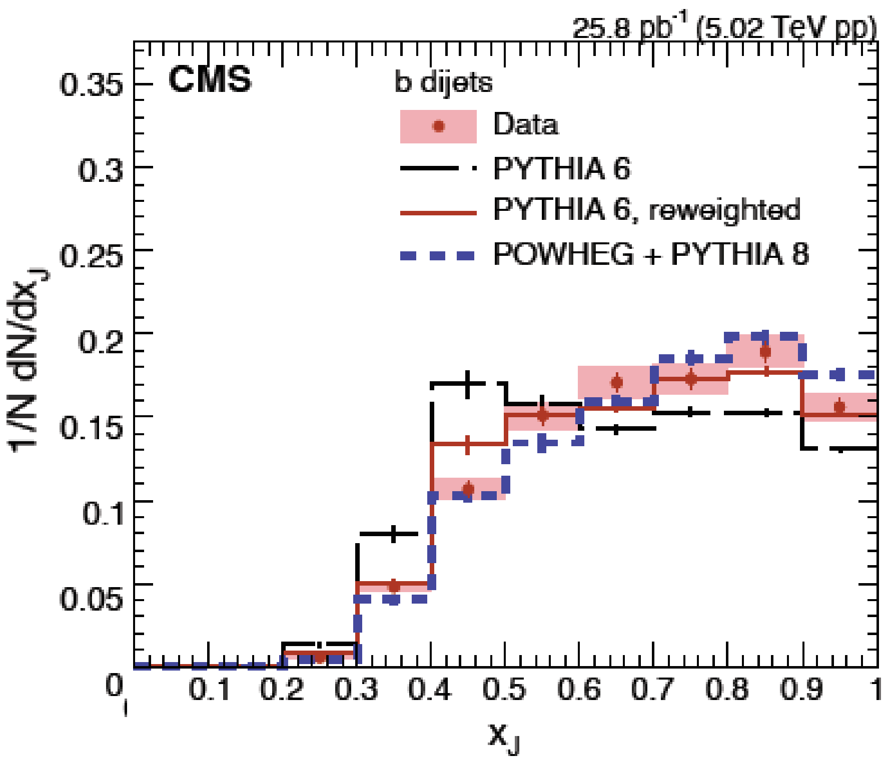


JHEP 03 (2018) 181

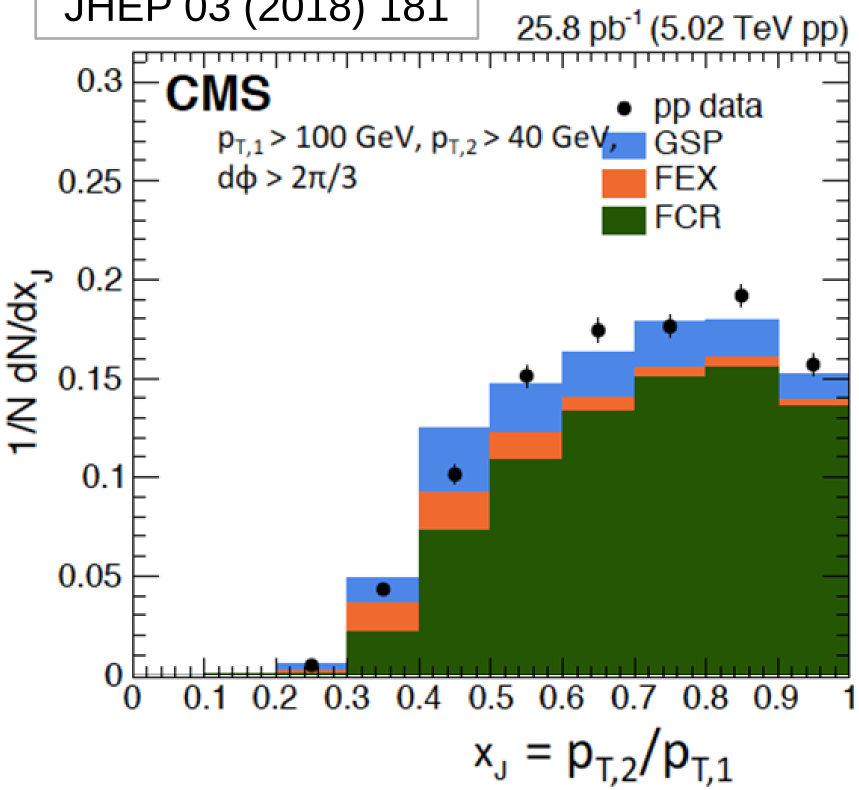


- Quenching is similar for inclusive jest and beauty-jets
- Theory calculations the reproduce b-jet R_{AA} include radiative + collisional energy loss + CNM effects
- Beauty dijets: no significant differences in x_J distributions with inclusive dijets

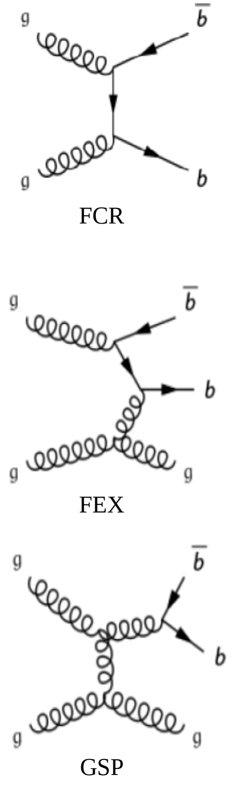
Semi-inclusive b-jets



JHEP 03 (2018) 181



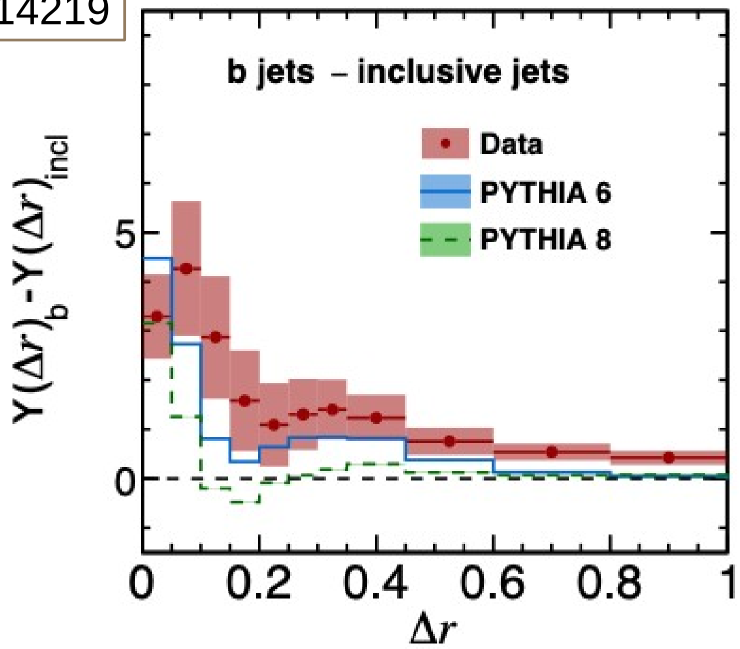
beauty

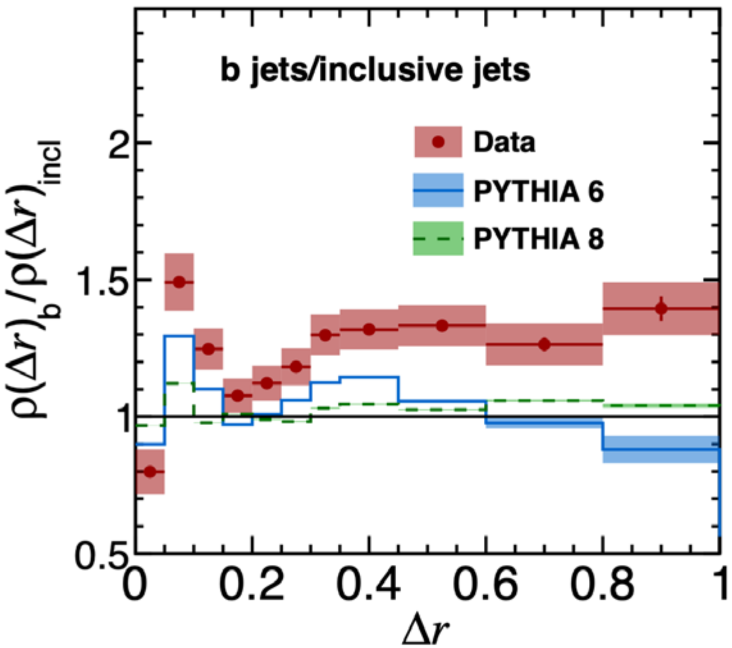


- Detailed x_J studies for beauty dijets:
  - → Most of beauty dijets come from FCR (b quark initiated) in QCD
- Data suggest that higher order contributions are important for b-jet production at LHC and are mismodeled in PYTHIA

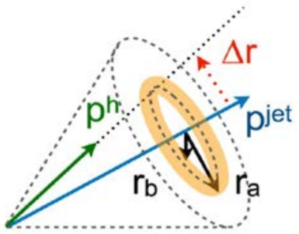
Beauty-jet constituents

arXiv:2005.14219





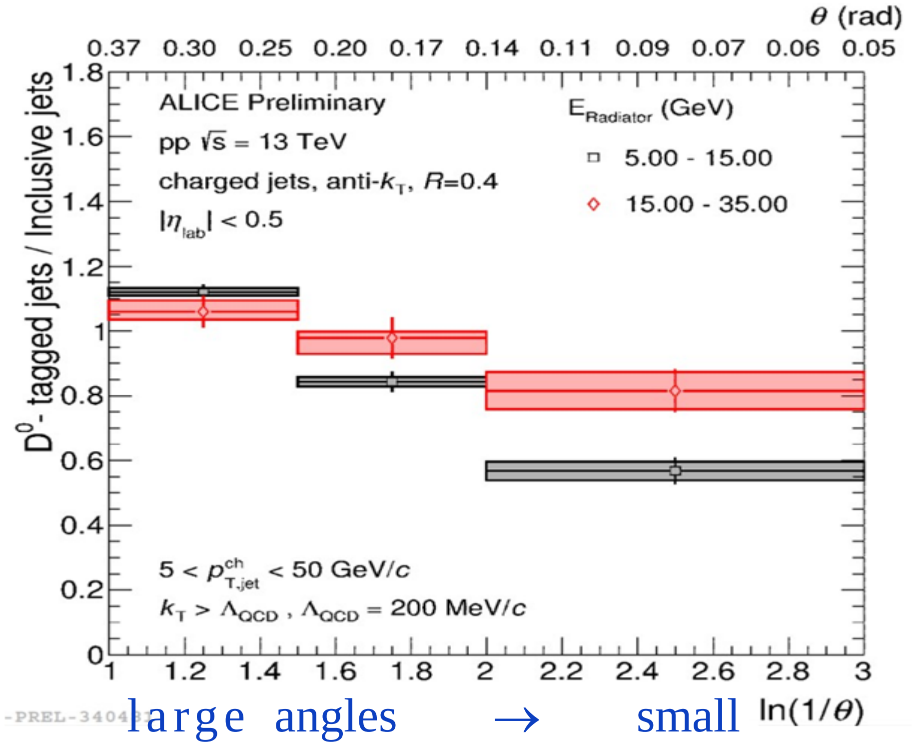
beauty

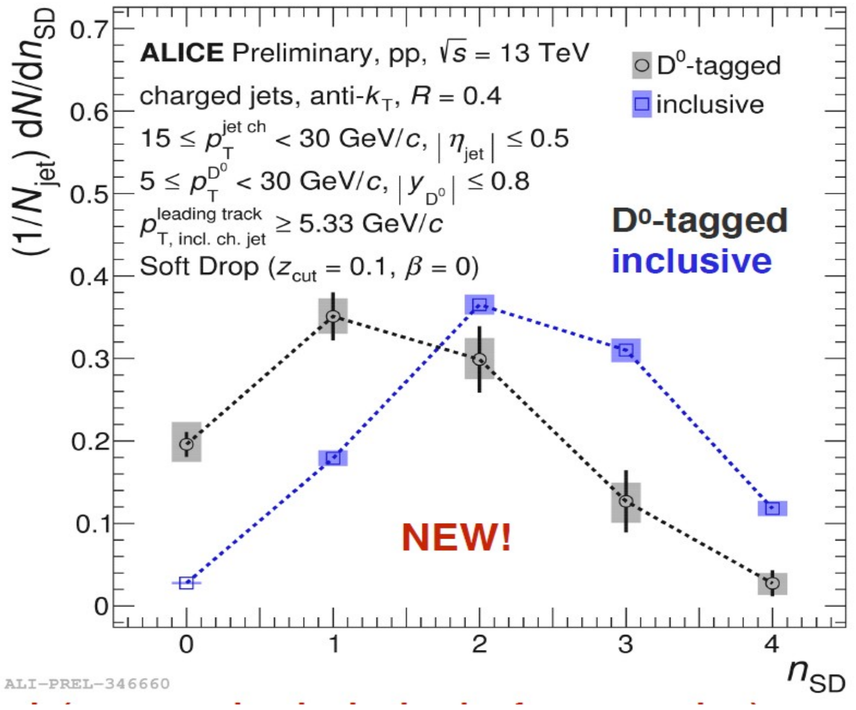


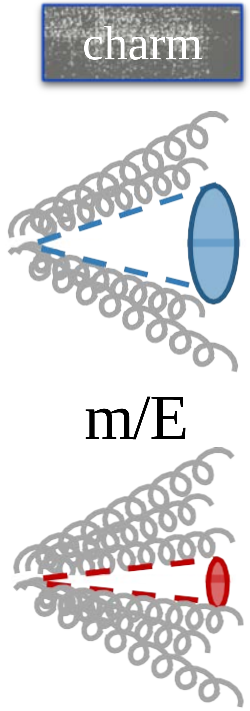
$$\rho(\Delta r) = \frac{1}{\delta r}\frac{\sum_{\text{jets}}\sum_{\text{particle}\in(\Delta r_a,\Delta r_b)} p_T^{\text{trk}}}{\sum_{\text{jets}}\sum_{\text{trk}} p_T^{\text{trk}}}$$

- Beauty jets constituent study: charged hadron yields and jet shapes
- Sensitive to production processes and fragmentation details
- Beauty-to-inclusive low-R structure: momentum shift further from axes (generally captured by PYTHIA) → dead-code effect?
- Broader shapes at large R (not reproduced by PYTHA) → radiative corrections? GSP mis-modeling?

Charm-jet constituents

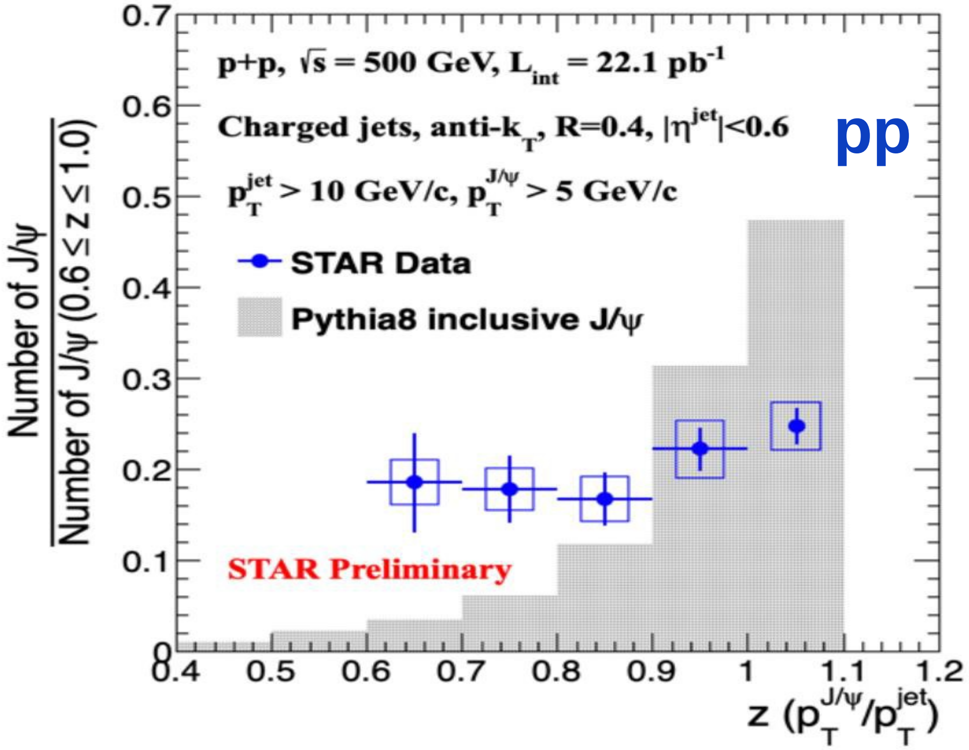


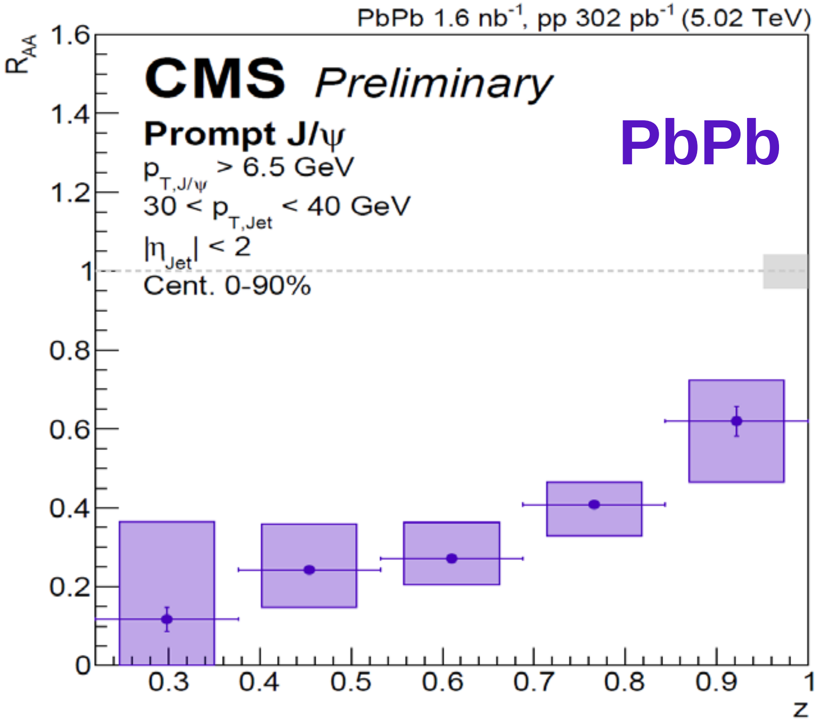




- Dead-cone effect is expected source of flavor hierarchy in energy loss
- D^0-tagged in 13TeV pp: suppression of radiation in jets towards at low angles
- Charm jets vs inclusive jets n_{SD}: harder fragmentation for heavy quarks

J/ψ Production in Jets



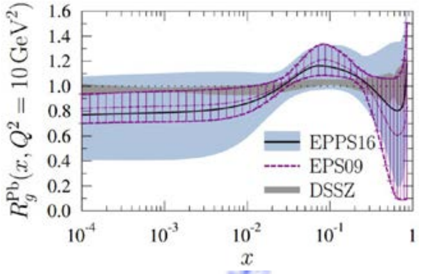


charm

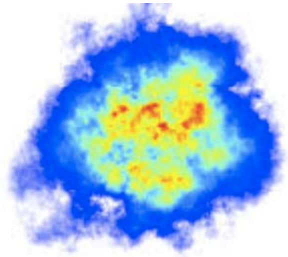
- 500 GeV pp, fragmentation function: J/ψ produced less isolated compared to PYTHIA
- 5 TeV PbPb, R_{AA}: more suppression for less-isolated J/ψ than for isolated

Summary and Outlook

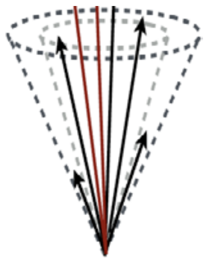
- Wealth of experimental data on heavy flavor production and faith in the medium



- Initial state:
  - HF nPDF constraints down to x^{-5} but precision is still limited
  - Possible tension in p_T dependence of D^0 R_{FB} and nPDF calculations
- HF collectivity … everywhere:
  - Flavor hierarchy in AA collisions: $v_2(\text{light}) \gtrsim v_2(c) > v_2(b)$, $v_3(\text{light}) > v_3(c) > v_3(b) \approx 0$
  - High multiplicity pp and pA: $v_2(\text{light}) > v_2(c) > v_2(b) \approx 0$



- Nuclear Modification: Flavor hierarchy at intermediate p_T: $R_{AA}(b) > R_{AA}(c) \approx R_{AA}(\text{light})$
- Hadronization: baryon/meson enhancement in AA and pp wrt. e^+e^-, strangeness enhancement
- HF jets: new constraints on production mechanisms, dead-cone effect and fragmentation details

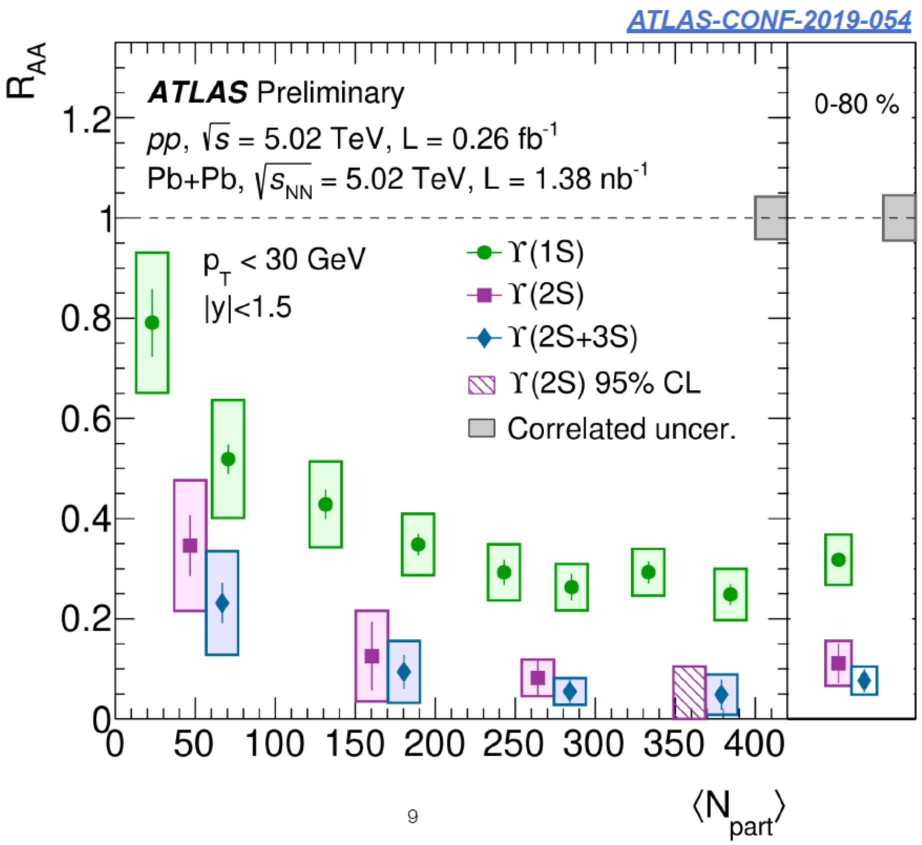


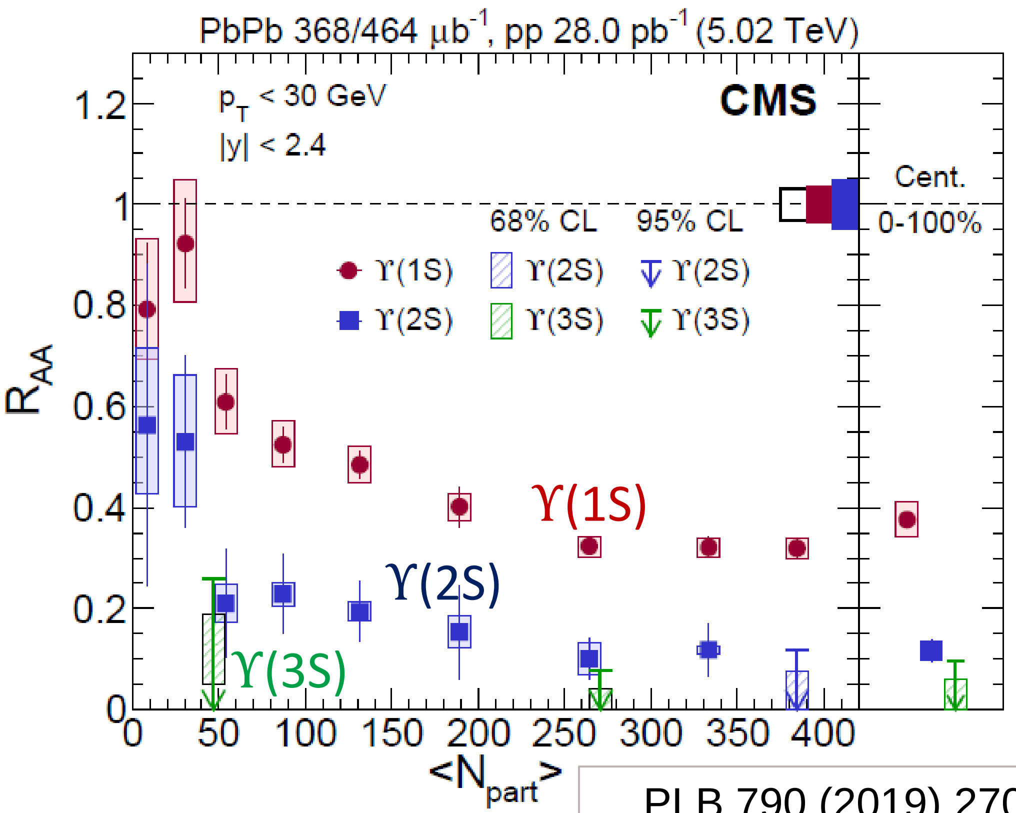
- More work to be done!

Thank you!

The UIC Group's work is supported by DOE-NP

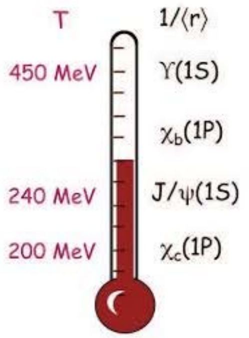
Quarkonia in HI collisions





PLB 790 (2019) 270

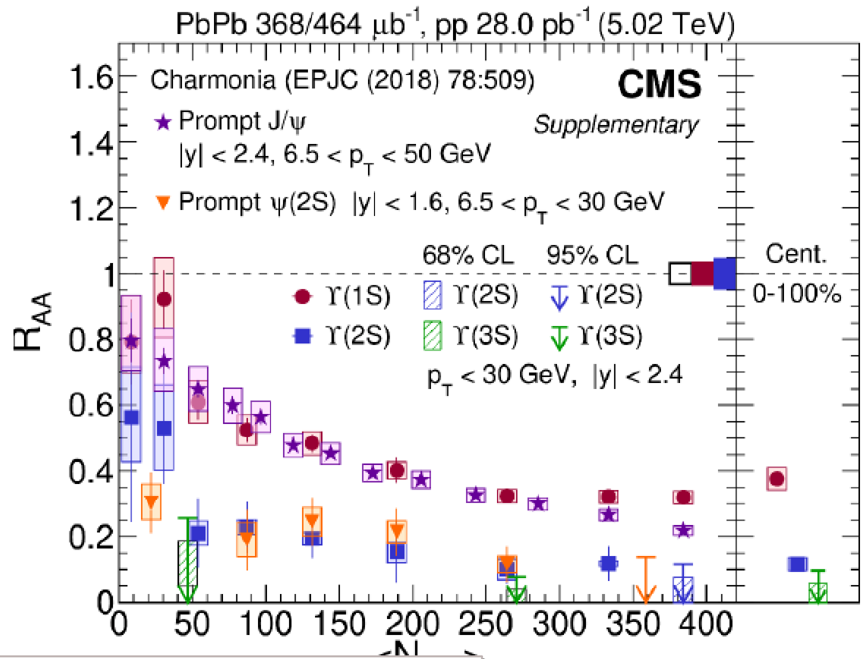
$$R_{AA} = \frac{\mathrm{Yield}_{AA}/\langle N_{binary}\rangle_{AA}}{\mathrm{Yield}_{pp}}$$



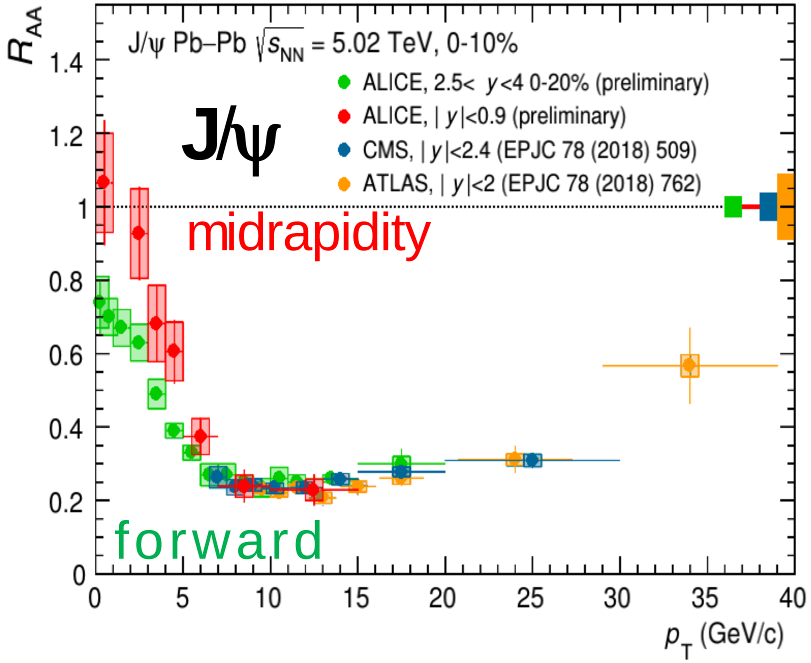
- Sequential “melting” is established by the hierarchy of Upsilon states suppression
- Binding energy range probes medium temperature and its centrality dependence

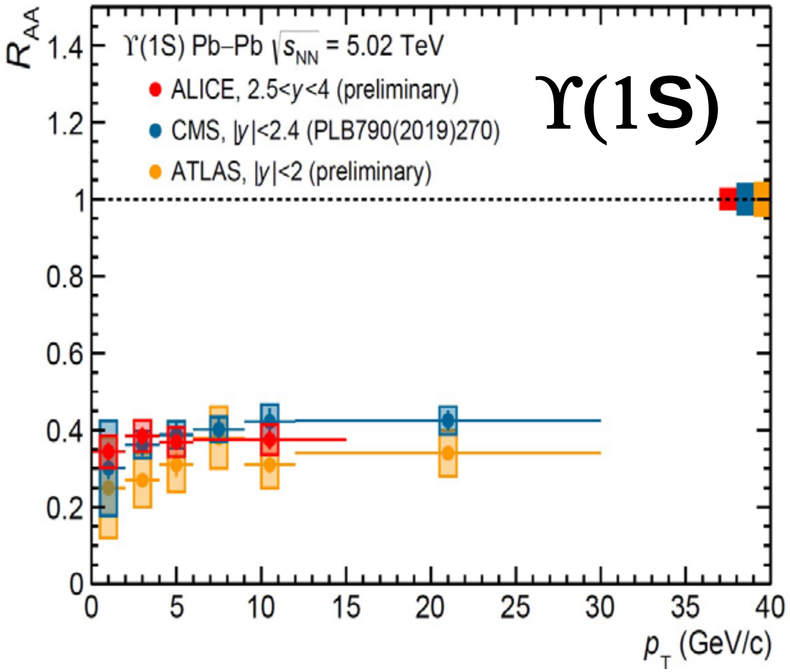
Quarkonia in HI Collisions

- Comparing charm and bottom:



EPJC (2018) 78 509

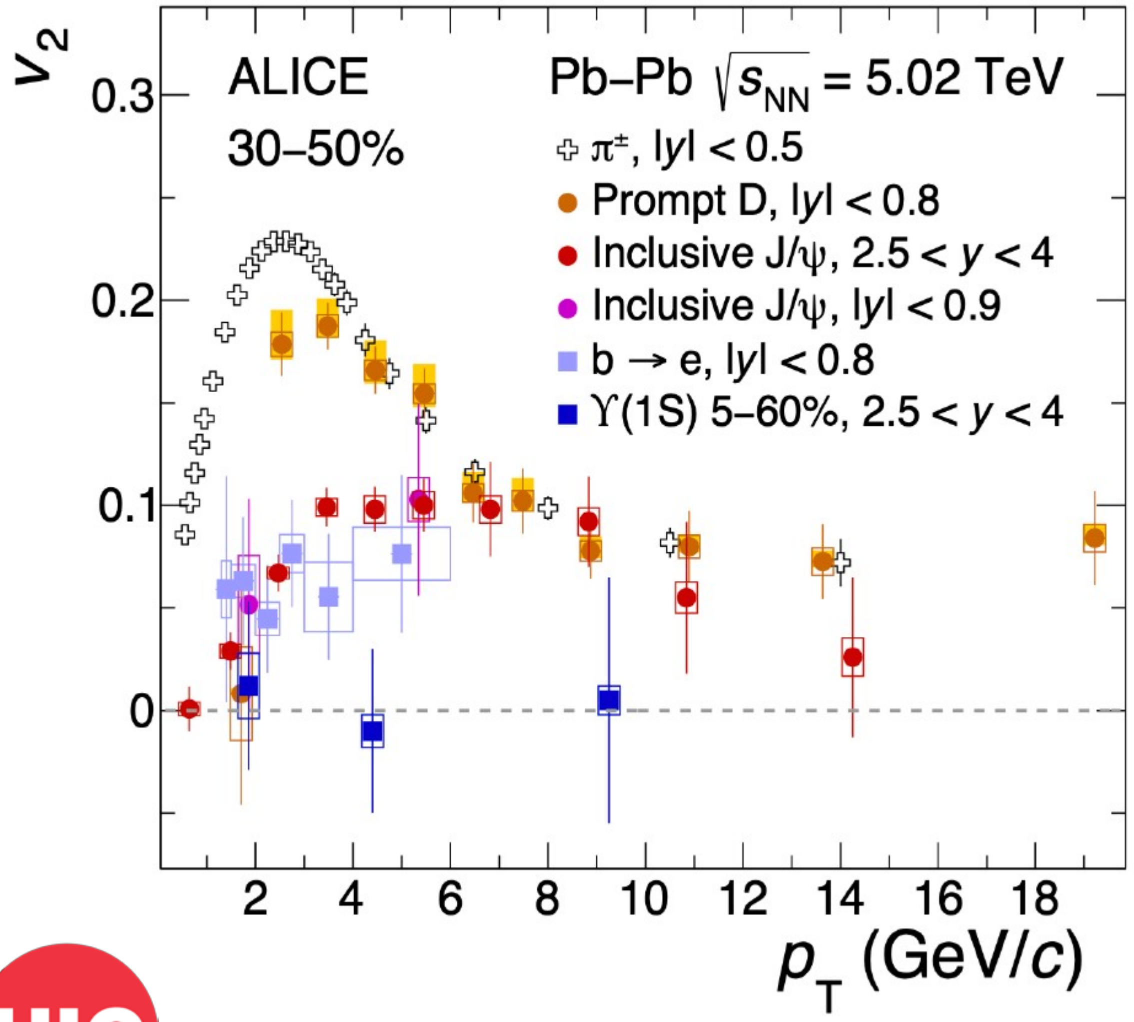




- Similar suppression levels are seen for prompt $\Psi(2s)$ and $\Upsilon(2S)$
- Similar suppression levels are seen for J/ψ and $\Upsilon(1S)$ as function of collisions centrality;

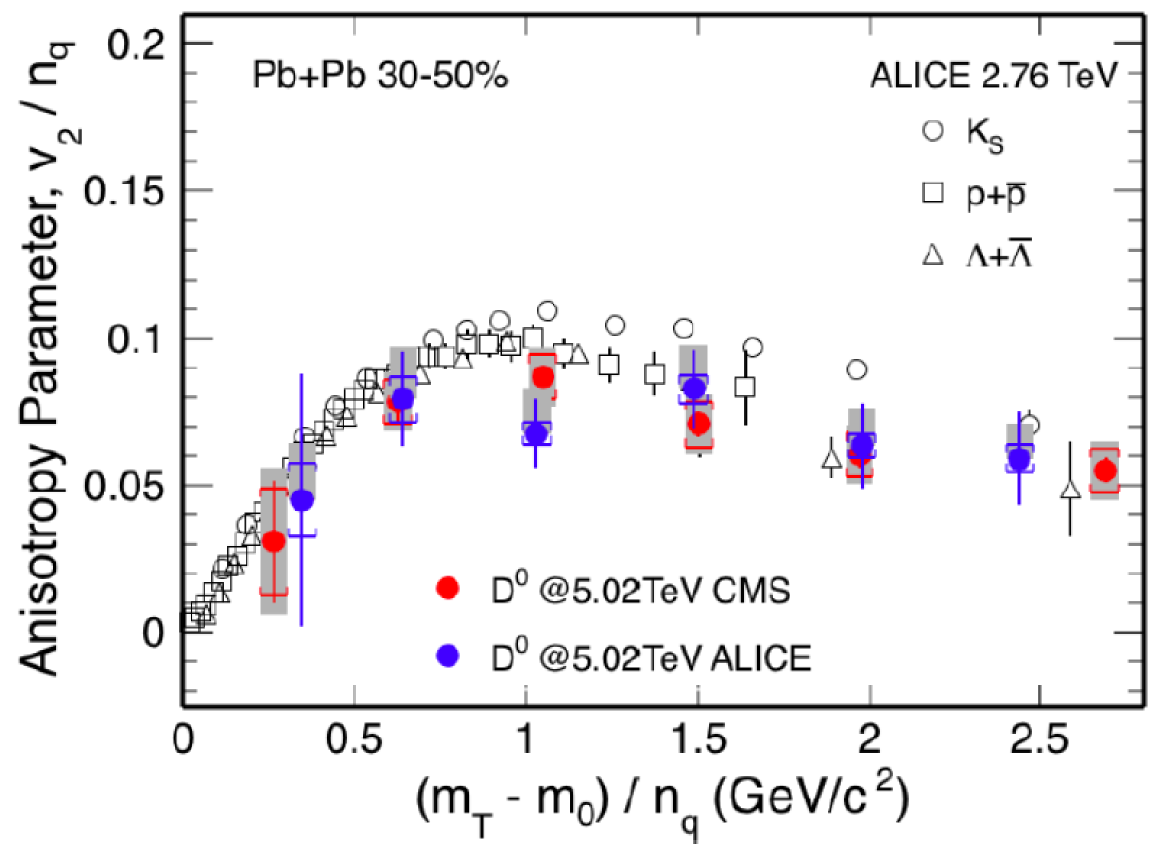
  but variations in trends at low p_T

Quarkonia v_2



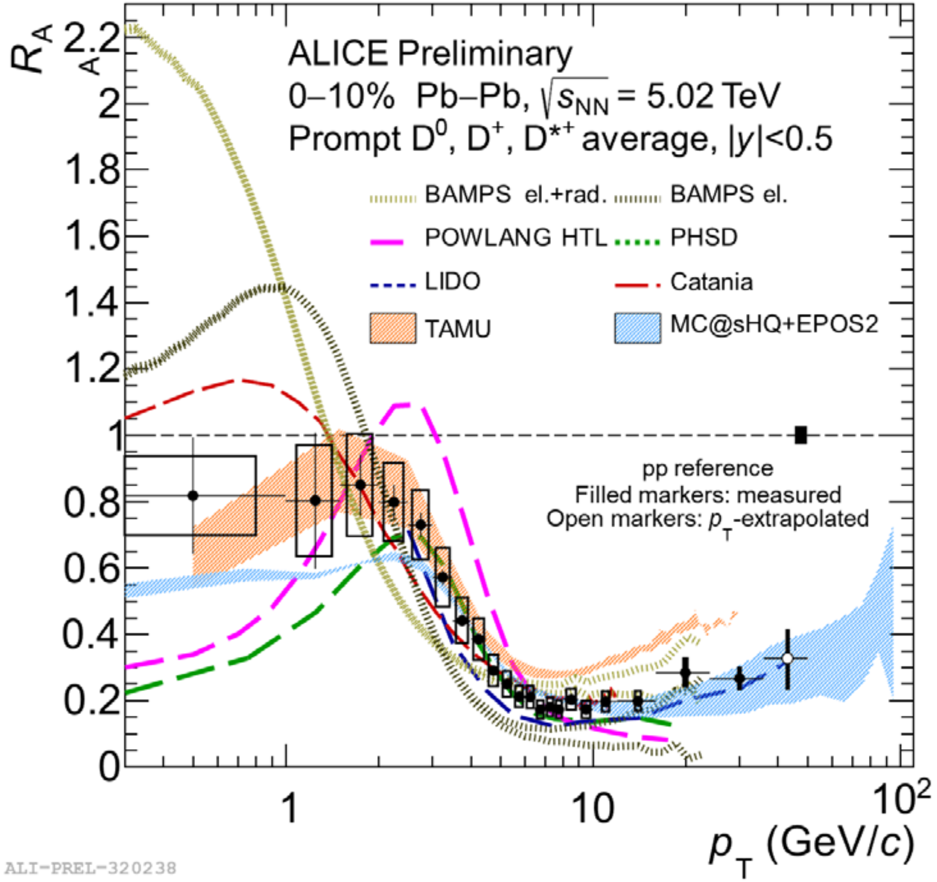
- Lower p_T: v_2(light) > v_2(D) > v_2(J/ψ) > v_2(Υ)~0
- High p_T: common trend for charm and open beauty but v_2(Υ)~0
- Large J/ ψ v_2 – consistent with significant recombination contributions
- Low/no Υ(1S) v_2 – not much recombination at play or (and) possible early-time Υ dissociation

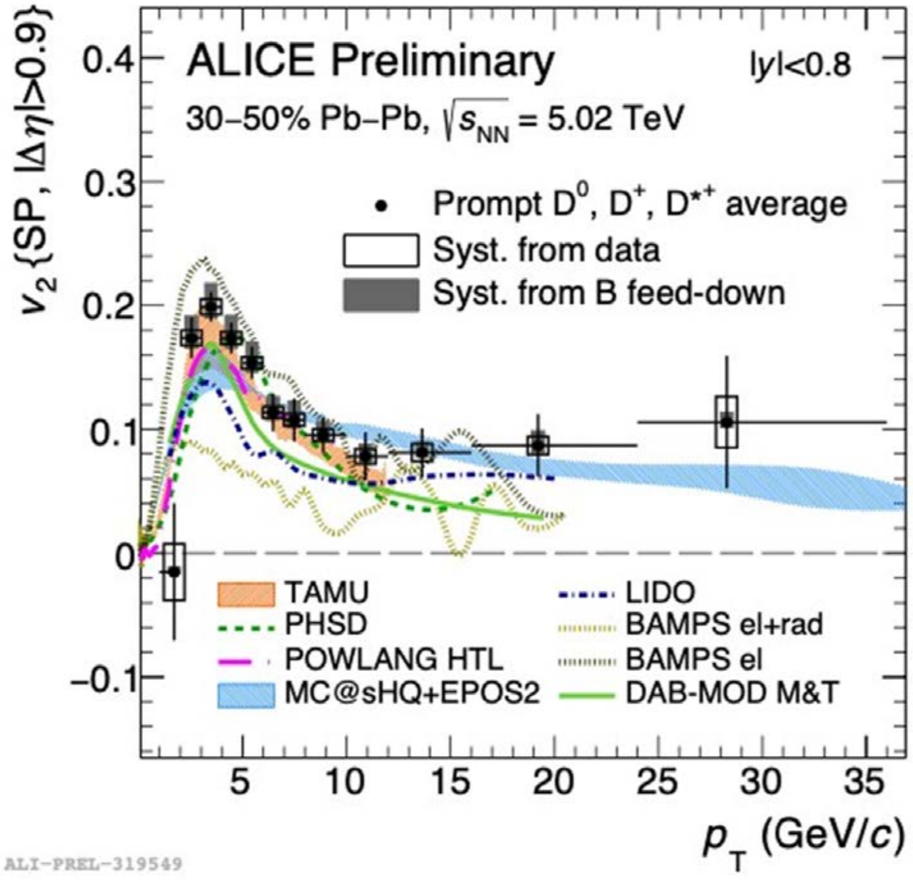
Charm v_2 Scaling at LHC



- LHC open charm results show similar NCQ trend for charm and light hadrons

Modeling R_{AA} and v_2 for charm

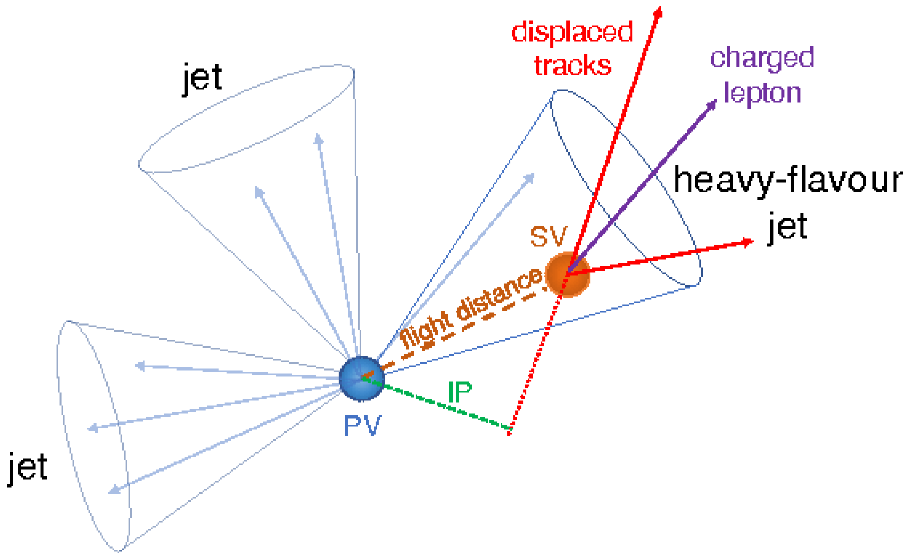


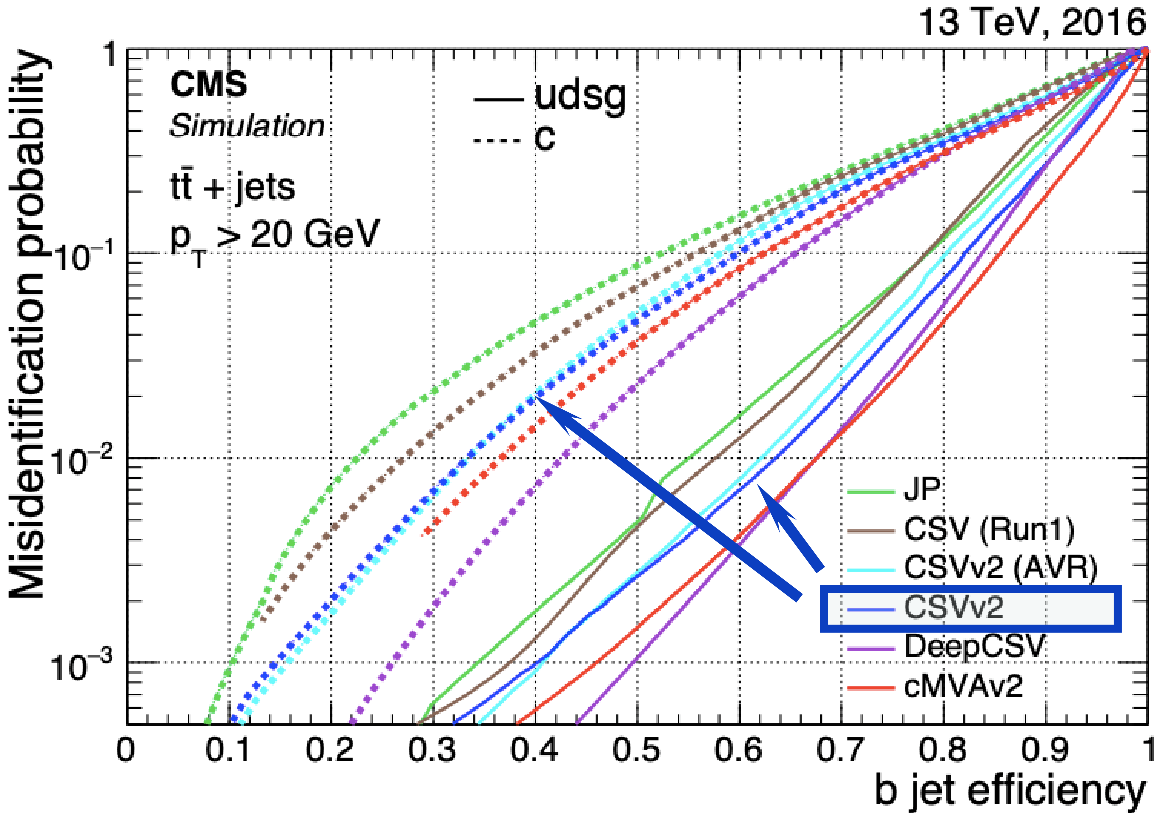


- Simultaneous description of charm R_{AA} and v_2 remains challenging for the models.
- Models that seem to do best include both collisional and radiative energy loss and nPDF effects (shadowing)

Finding b-jets

- CMS b-tagging: a multi-variate discriminator (CSVv2) based on track and secondary vertex (SV) input





- The b quark production from all types of processes is tagged, main contributions: