IOP Institute of Physics

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Recent open heavy flavor results from RHIC and LHC

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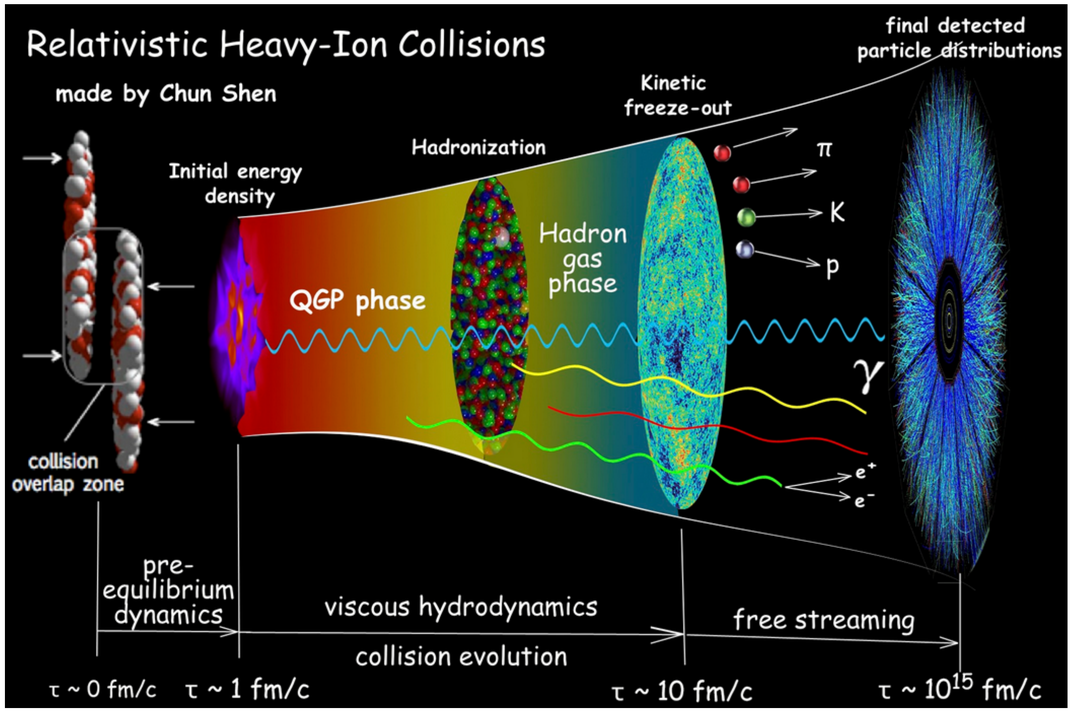
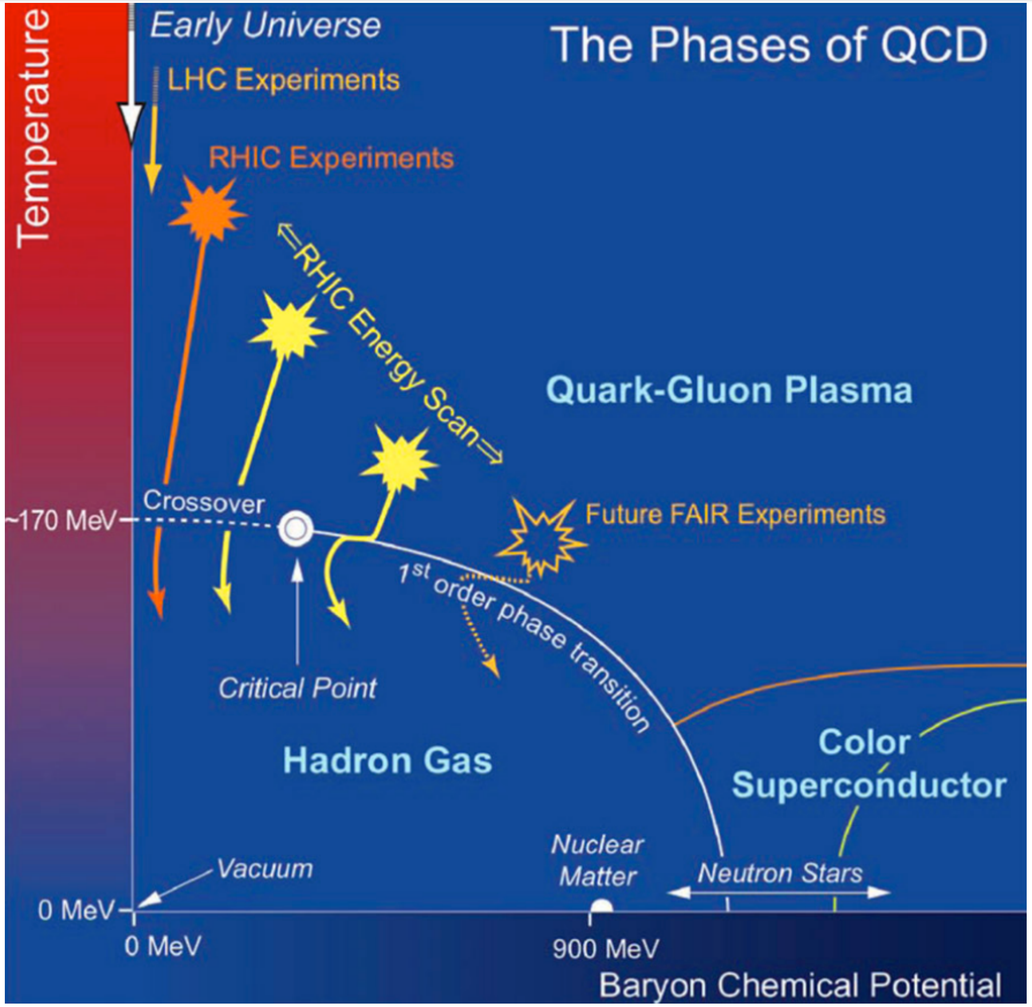
Heavy-ion collisions and Heavy Flavor quarks

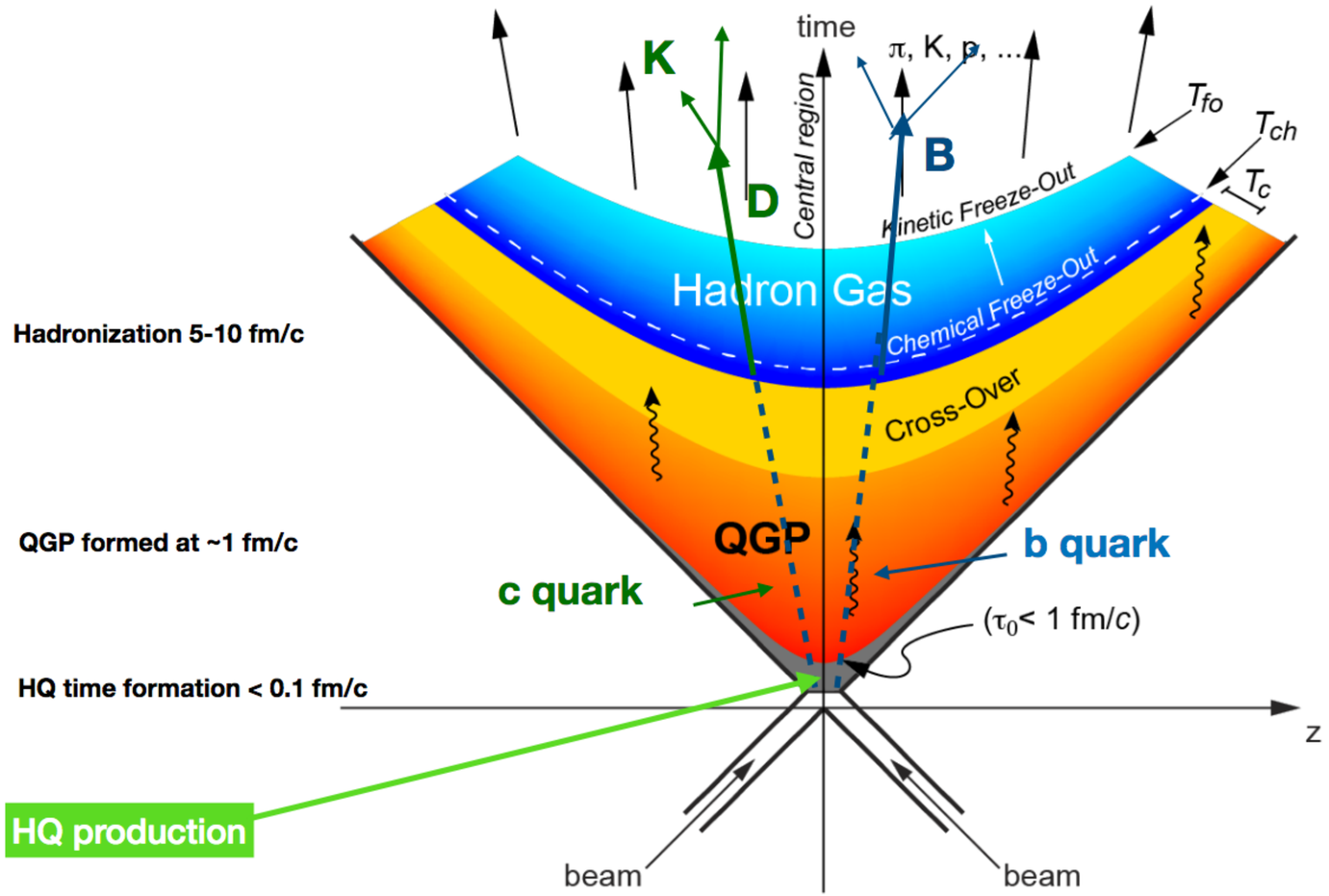




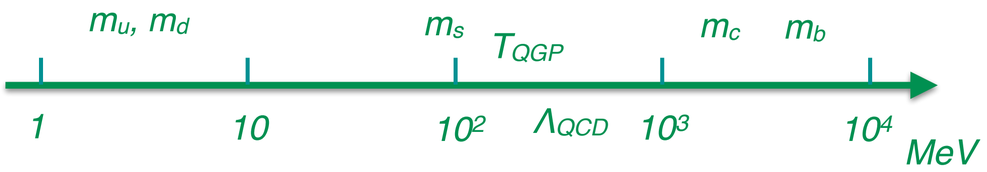
Relativistic Heavy Ion collisions: An excellent laboratory to study the QGP phase and QCD at extreme temepratures and energy densities

RHIC: Au+Au, $\sqrt{s_{NN}}$ = 200 GeV (Top energy)
LHC: Pb+Pb, $\sqrt{s_{NN}}$ = 2.76 TeV, 5.02 TeV

Heavy-ion collisions and Heavy Flavor quarks



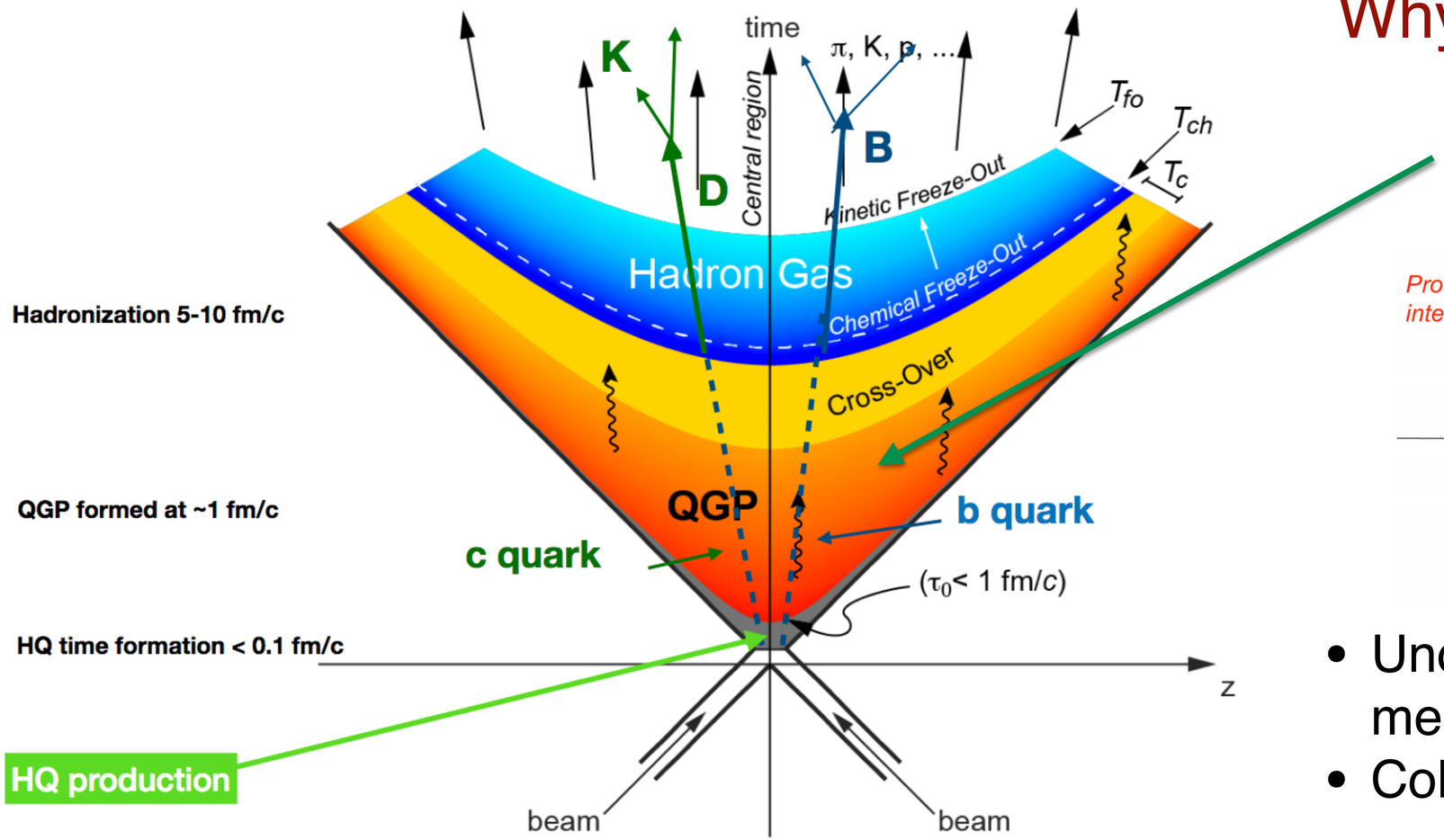
Why study heavy flavor quarks?



- Mass higher than T_{QGP}, Λ_{QCD}
- Produced predominantly in initial hard-scatterings
- Production cross-sections amenable to pQCD calculations

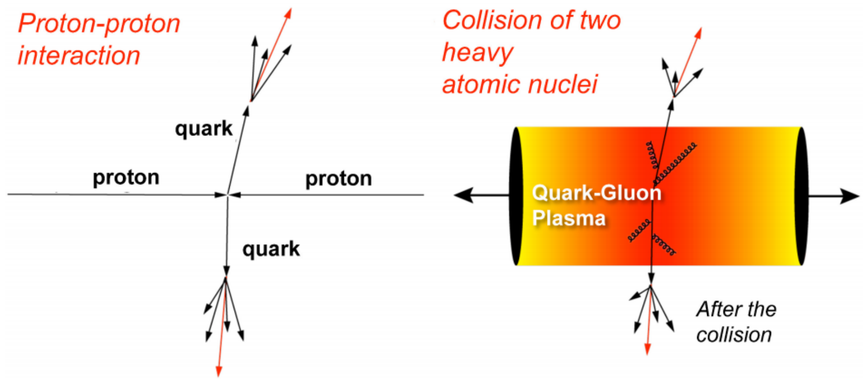
- Ideal probes to study QGP

Heavy-ion collisions and Heavy Flavor quarks



Why study heavy flavor quarks?

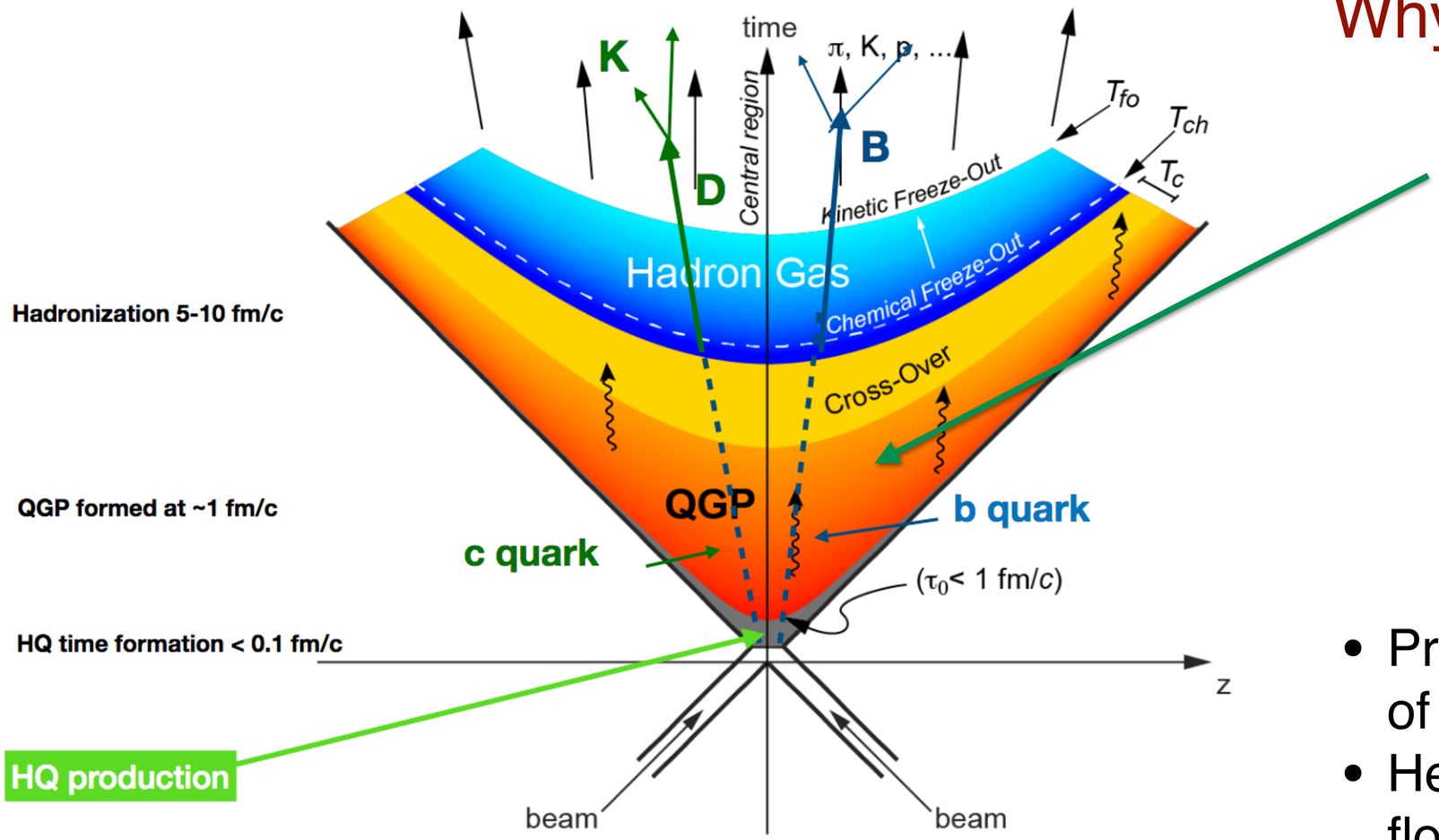
Energy loss in medium



- Understand parton energy loss mechanism in QGP
- Collisional and radiative energy loss

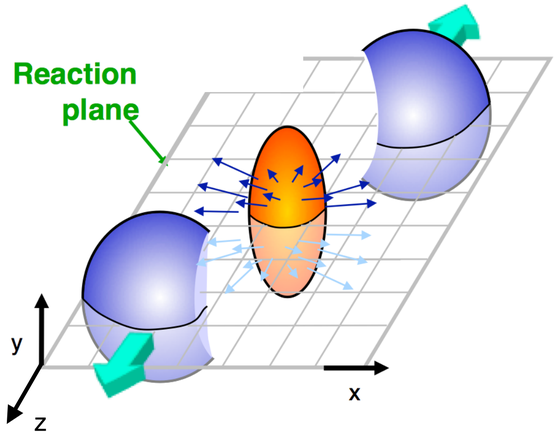
- Results in suppression of high p_T hadron production

Heavy-ion collisions and Heavy Flavor quarks



Why study heavy flavor quarks?

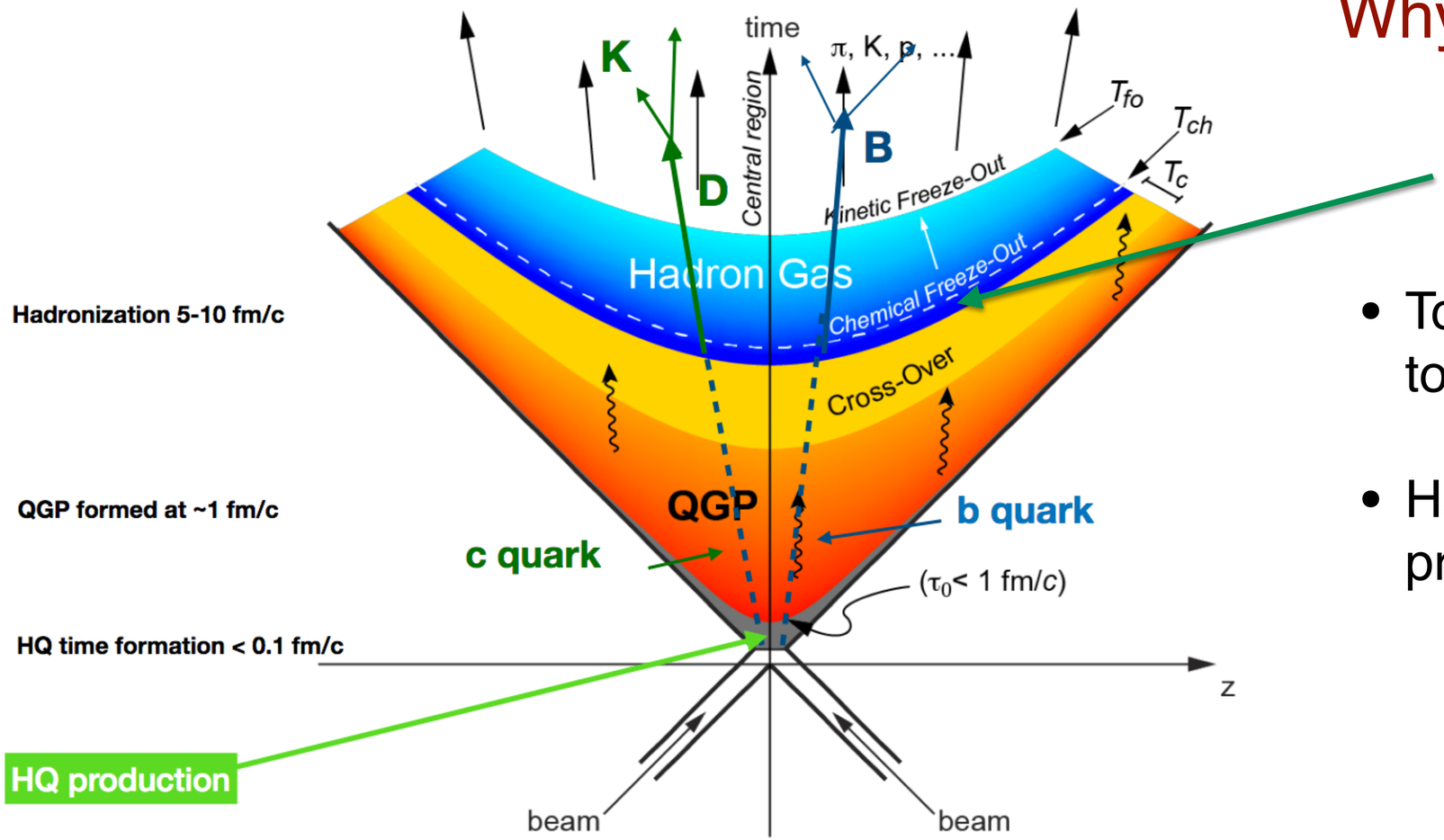
Anisotropic flow



- Pressure driven collective expansion of QGP medium
- Heavy quarks interact with and gain flow from QGP

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$$

Heavy-ion collisions and Heavy Flavor quarks

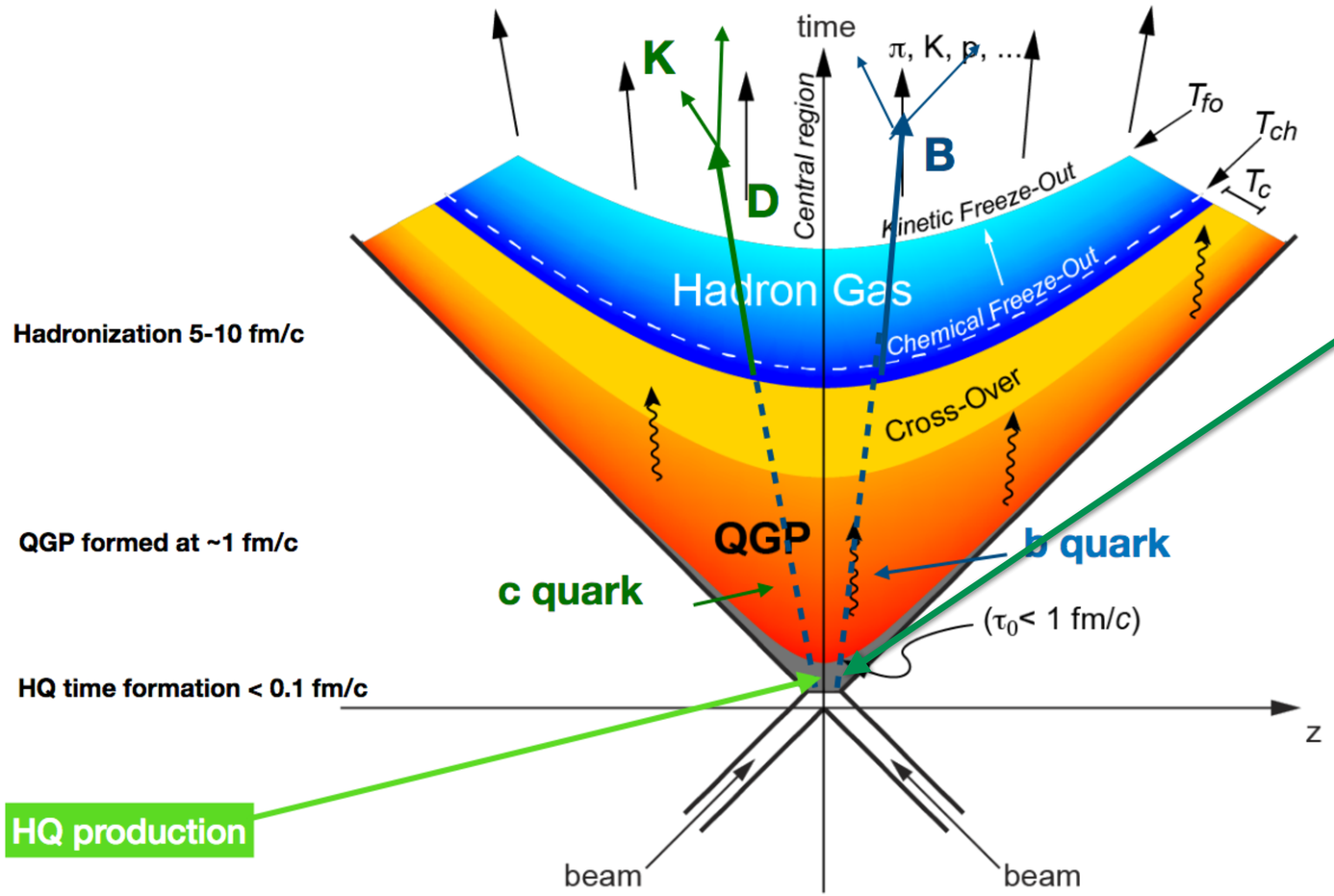


Why study heavy flavor quarks?

Hadronization

- Total HQ conserved - ideal probes to study hadronization
- Hadronization mechanism in the presence of QGP

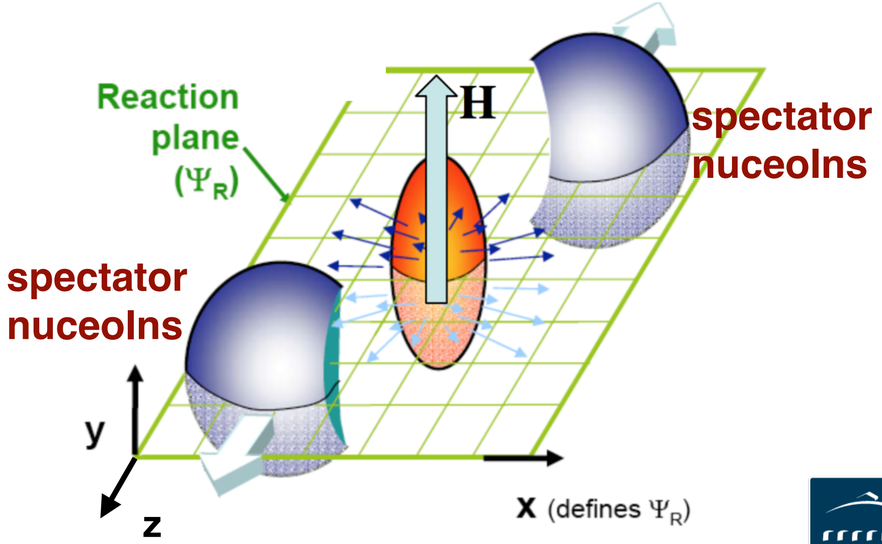
Heavy-ion collisions and Heavy Flavor quarks



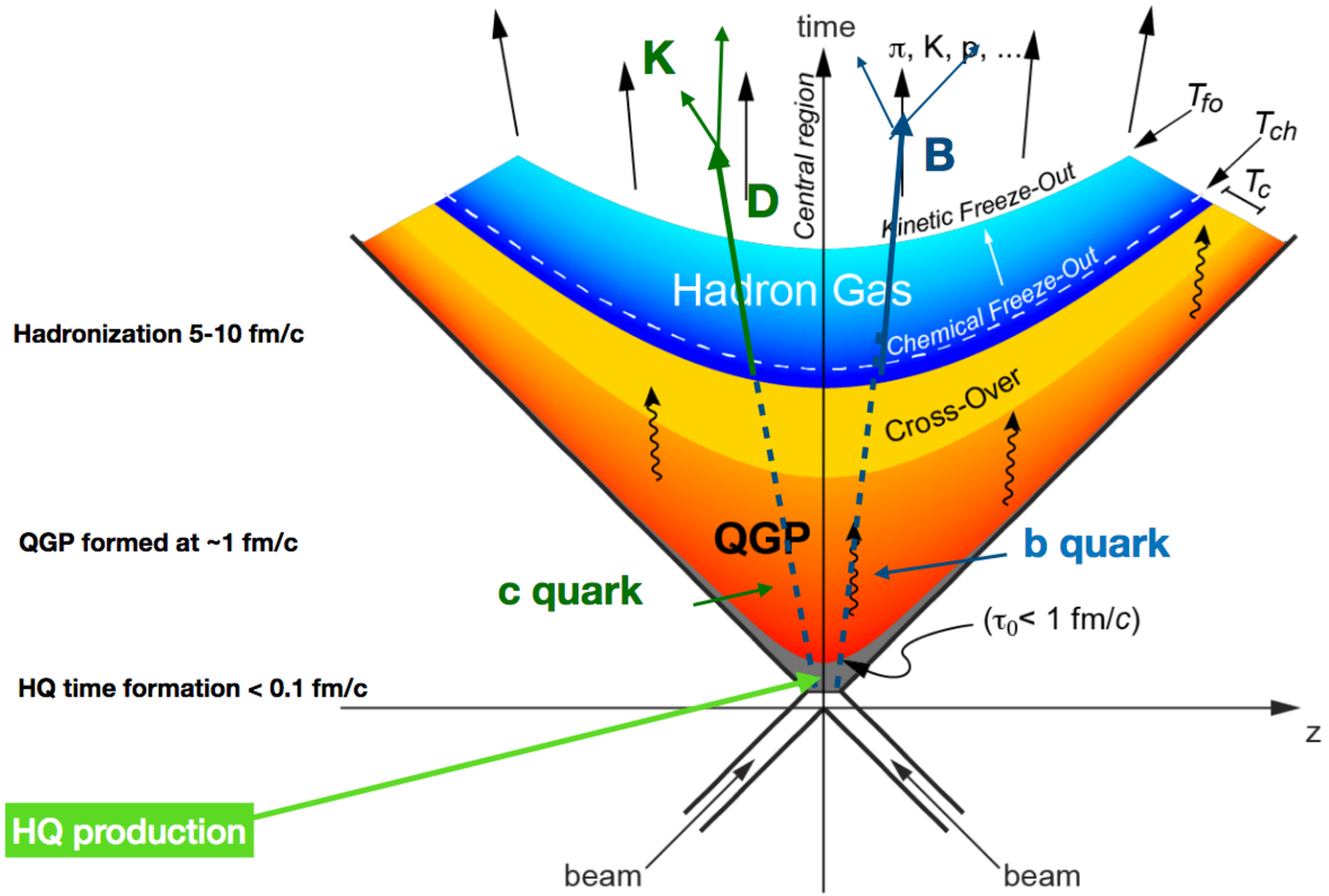
Why study heavy flavor quarks?

Initial conditions in HIC

- Large relaxation times - can carry information on initial conditions
- Probes of initial strong magnetic fields?



Heavy-ion collisions and Heavy Flavor quarks



Why study heavy flavor quarks?

Energy loss in medium

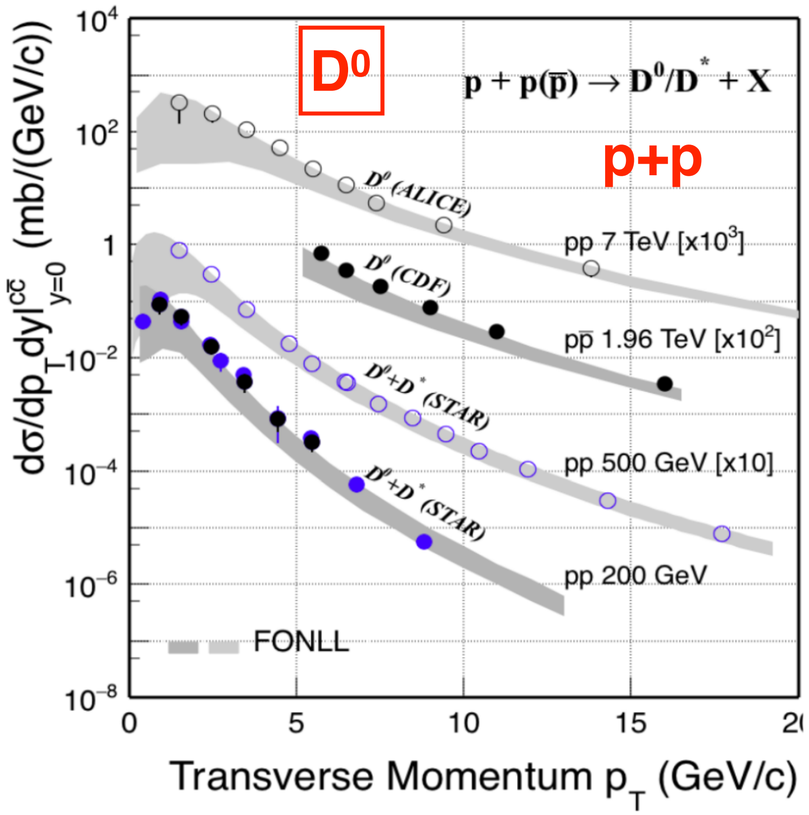
Anisotropic flow

Hadronization

Initial conditions in HIC

- **Wealth of new results from RHIC and LHC**

Heavy flavor production in p+p and p+A



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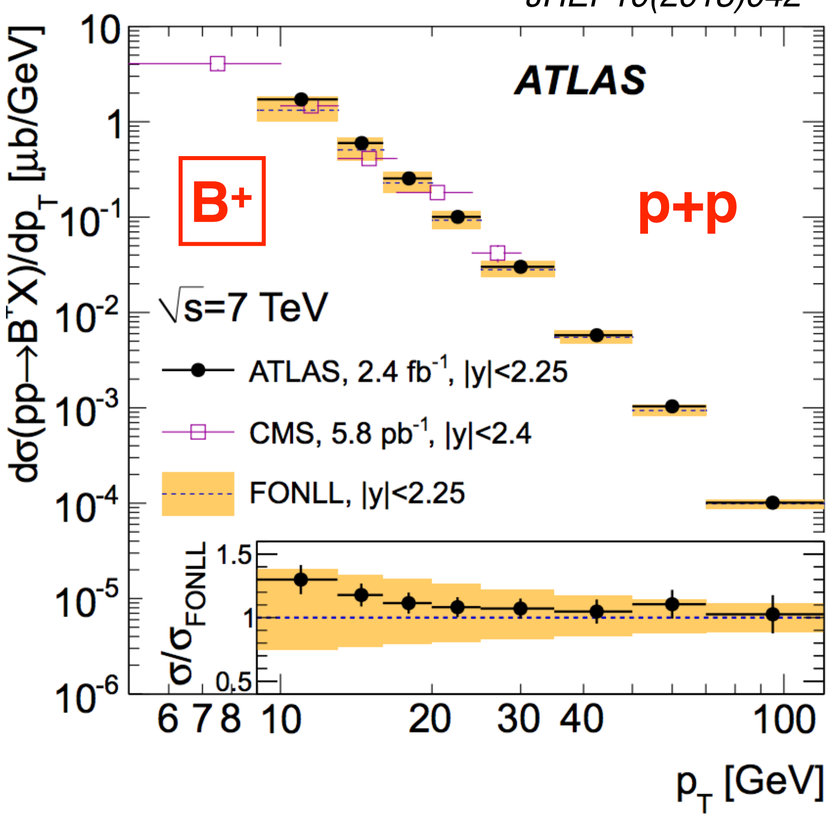
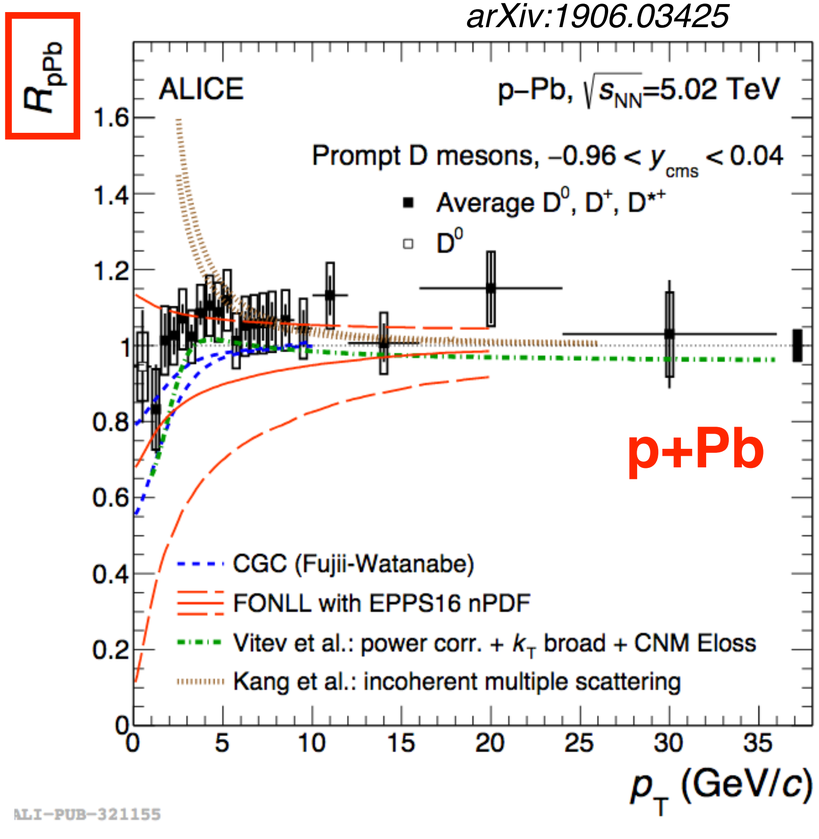


arXiv:1906.03425



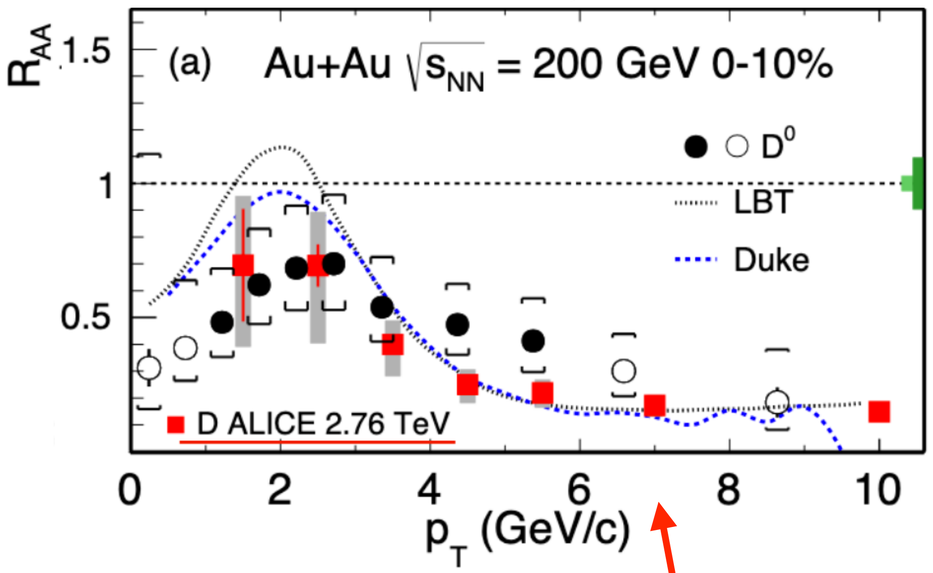
- Heavy flavor production in p+p collisions well described by pQCD calculations
- Measured values close to upper edge of FONLL uncertainty bands

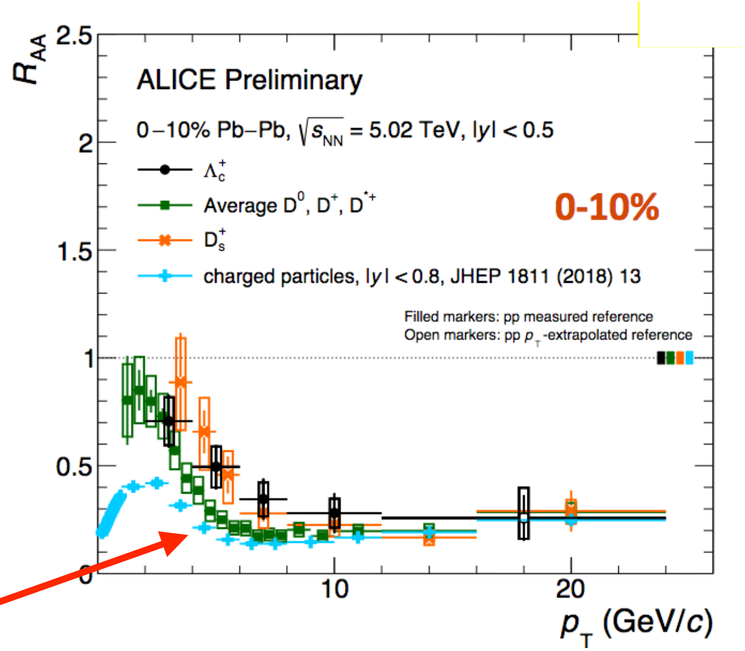
$$R_{pPb} = \frac{1}{N_{binary}^{pPb}} \frac{dN_{pPb}/dp_T}{dN_{pp}/dp_T}$$

- Small system size in p+A collisions
- No suppression seen in p+A within uncertainties

Suppression in A+A collisions

Phys. Rev. C 99, 034908





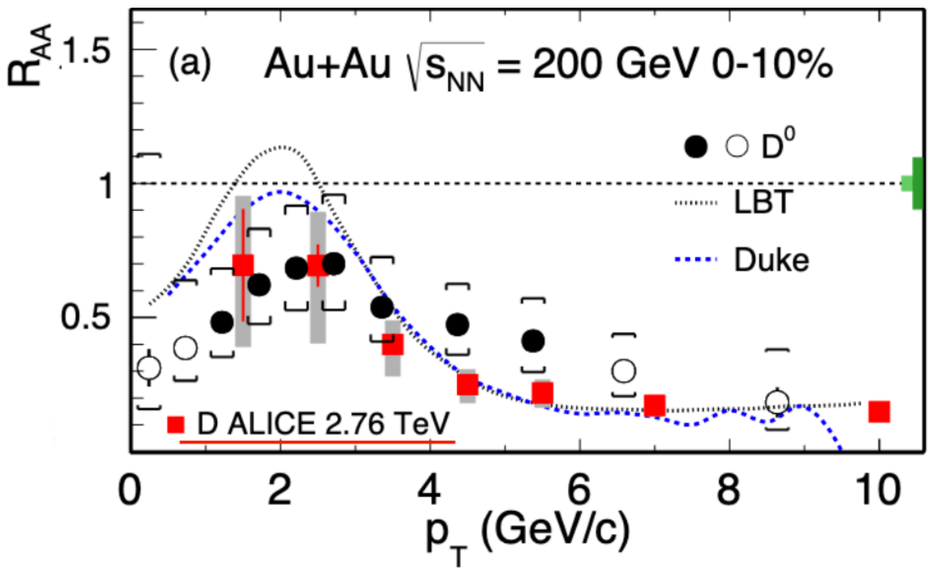
- Strong suppression of high p_T charm meson production in A+A collisions
- Strong interactions and energy loss of charm quarks in QGP

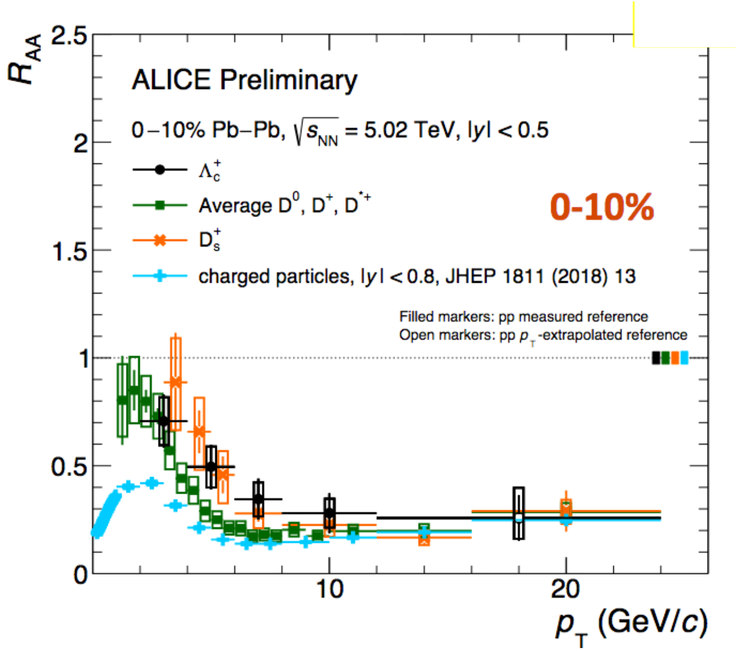
- Seen for all charm hadrons

$$R_{AA}(p_T) \equiv \frac{dN_{AA}/dp_T}{N_{binary}^{AA} \times dN_{pp}/dp_T}$$

Suppression in A+A collisions

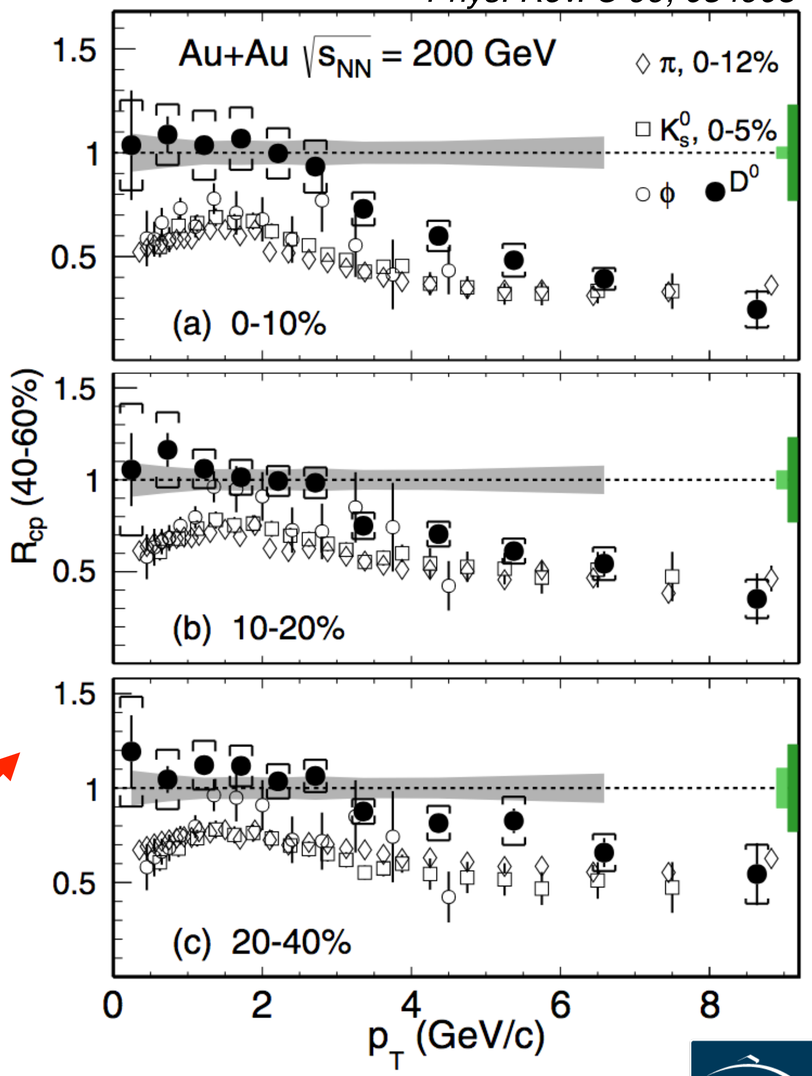
Phys. Rev. C 99, 034908





$$R_{CP} = \frac{N_{\text{binary}}^{\text{peripheral}}}{N_{\text{binary}}^{\text{central}}} \frac{dN_{\text{central}}/dp_T}{dN_{\text{perpheral}}/dp_T}$$

Phys. Rev. C 99, 034908



- Strong suppression of high p_T charm meson production in A+A collisions
- Strong interactions and energy loss of charm quarks in QGP

- Seen for all charm hadrons
- Suppression decrease towards peripheral collisions

Suppression in A+A collisions

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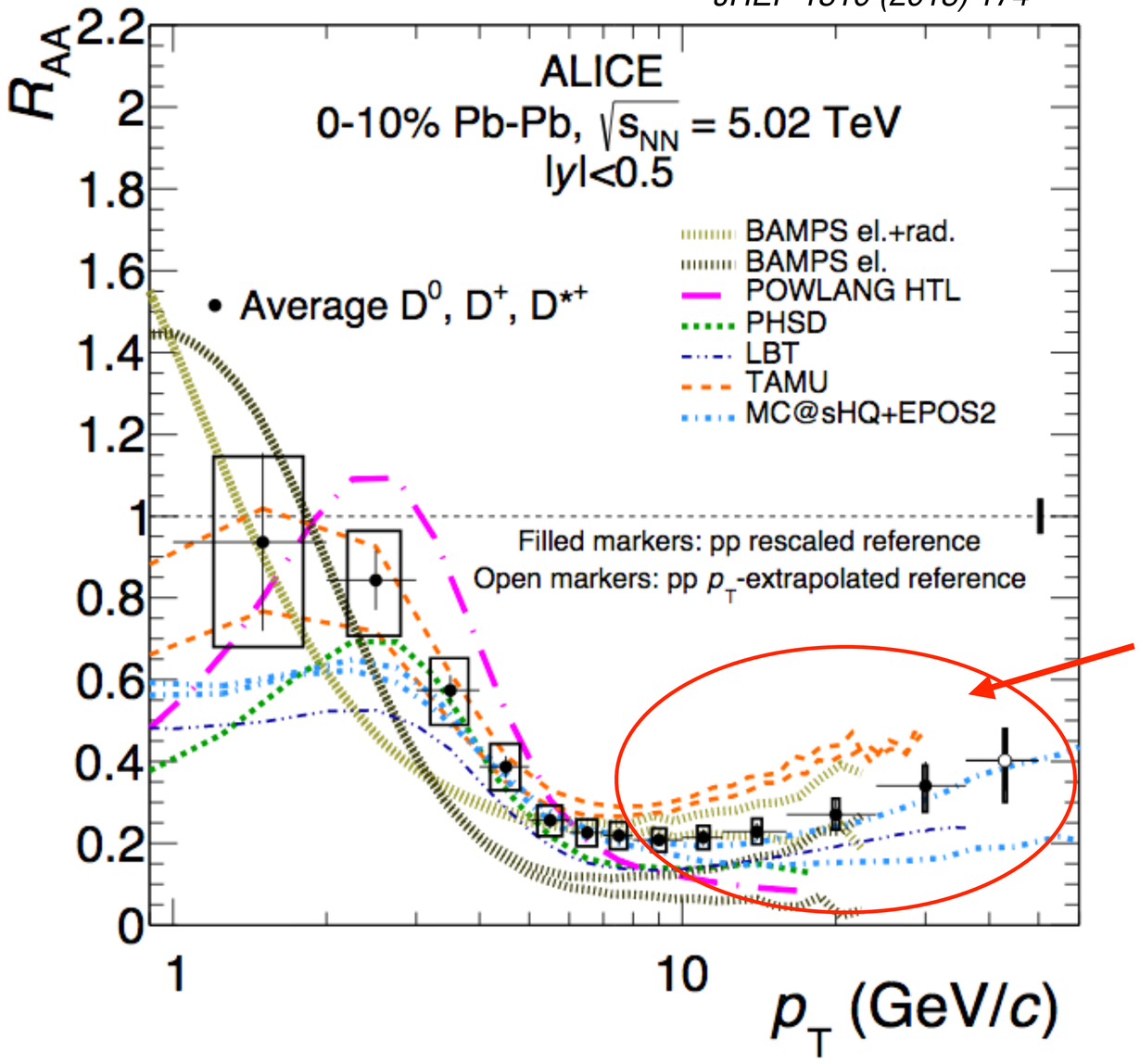
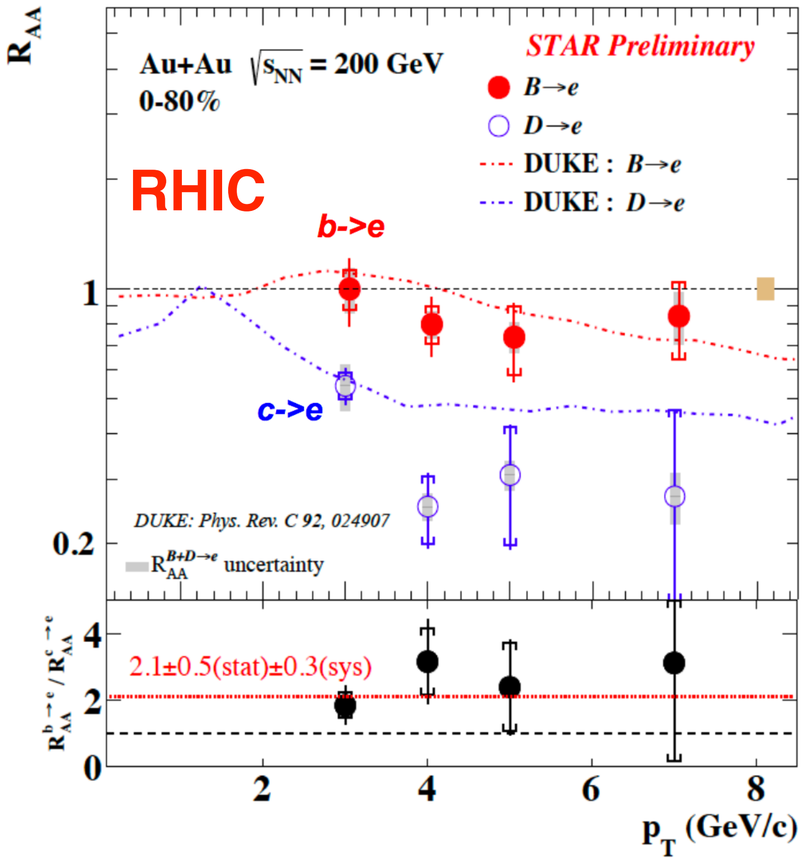


- Transport models with pQCD cross-sections (BAMPS, PHSD, MC@sHQ, LBT, POWLANG) and lattice QCD inspired interaction potentials (TAMU)
- Radiative energy loss start to dominate at higher p_T, interplay of collisional and radiative at lower p_T
- Models without radiative energy loss (POWLANG, BAMPS el, TAMU) deviate from data around $p_T \sim 10$ GeV/c

Mass dependence of suppression

- Energy loss expected to have a mass heirarchy: $\Delta E_b < \Delta E_c < \Delta E_{u,d}$



- Hint of less suppression of b—>e compared to c—>e at RHIC

Mass dependence of suppression

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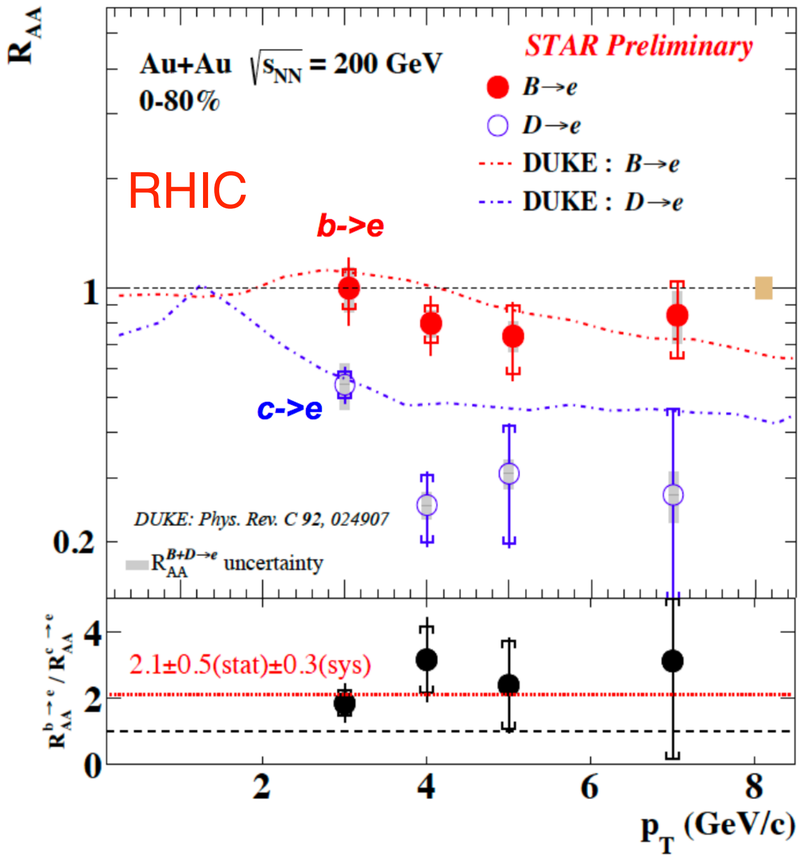
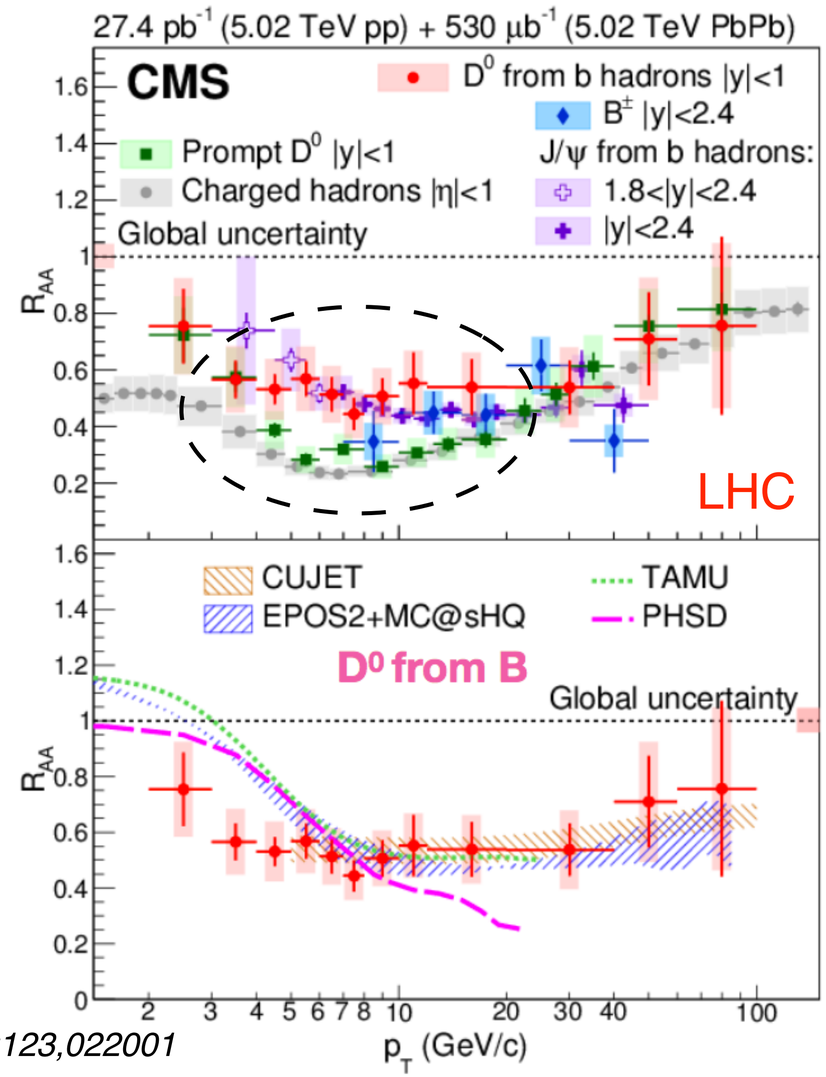


- R_{AA} of prompt D^0 (charm hadrons) and non-prompt D^0 and J/Psi (from B hadron decays) at LHC



Phys.Rev.Lett:123,022001

- Hint of less suppression of b—>e compared to c—>e at RHIC
- Less suppression of B hadrons than D hadrons at LHC

Mass dependence of suppression

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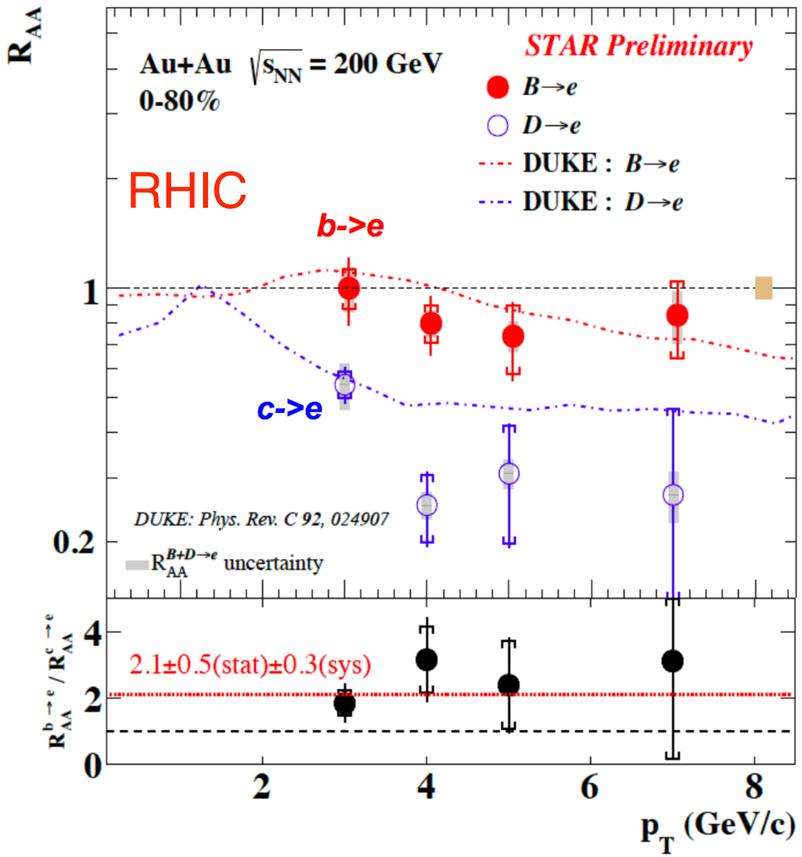
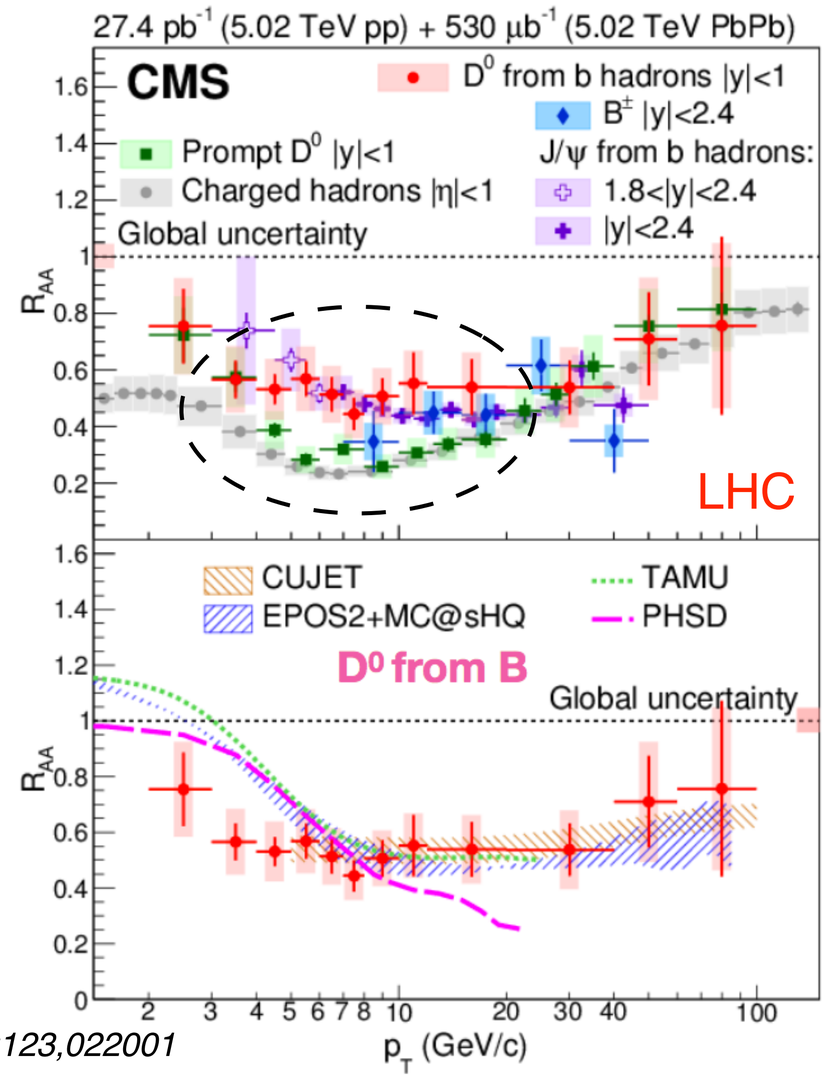


- R_{AA} of prompt D^0 (charm hadrons) and non-prompt D^0 and J/Psi (from B hadron decays) at LHC

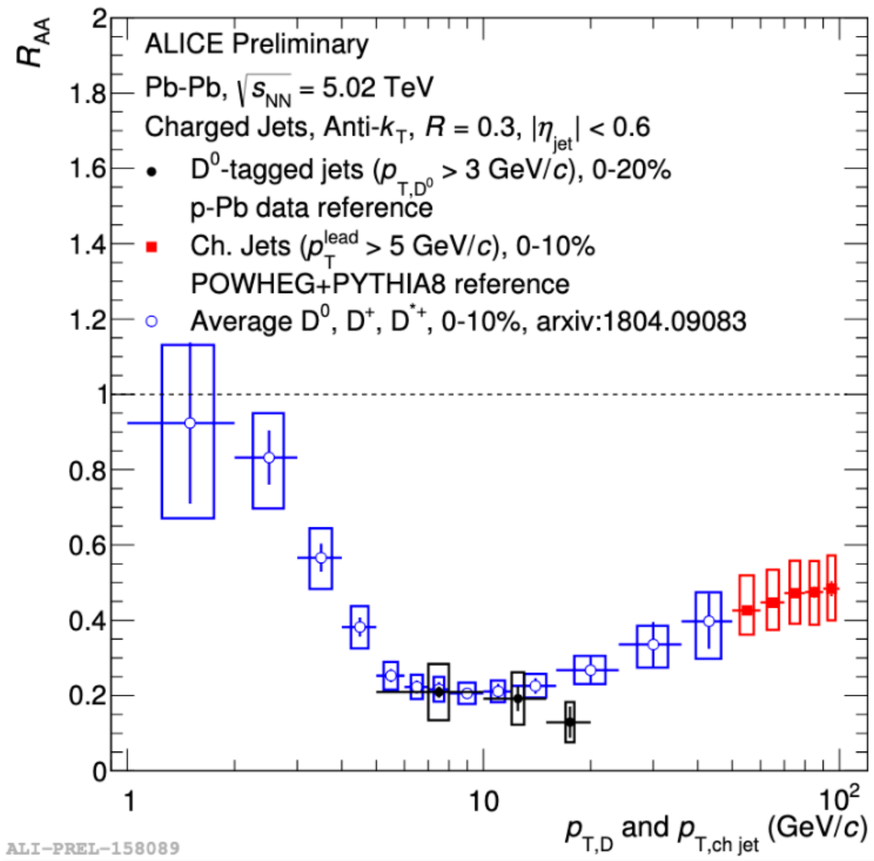
But multiple effects at play:
differences in spectra, energy loss, modifications of fragmentation, hadronization

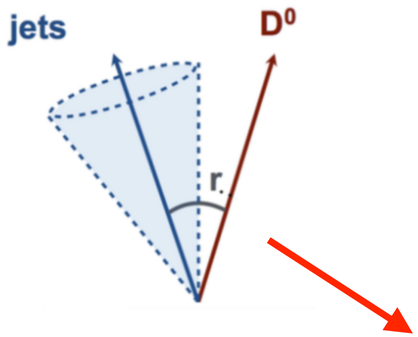


Phys.Rev.Lett:123,022001

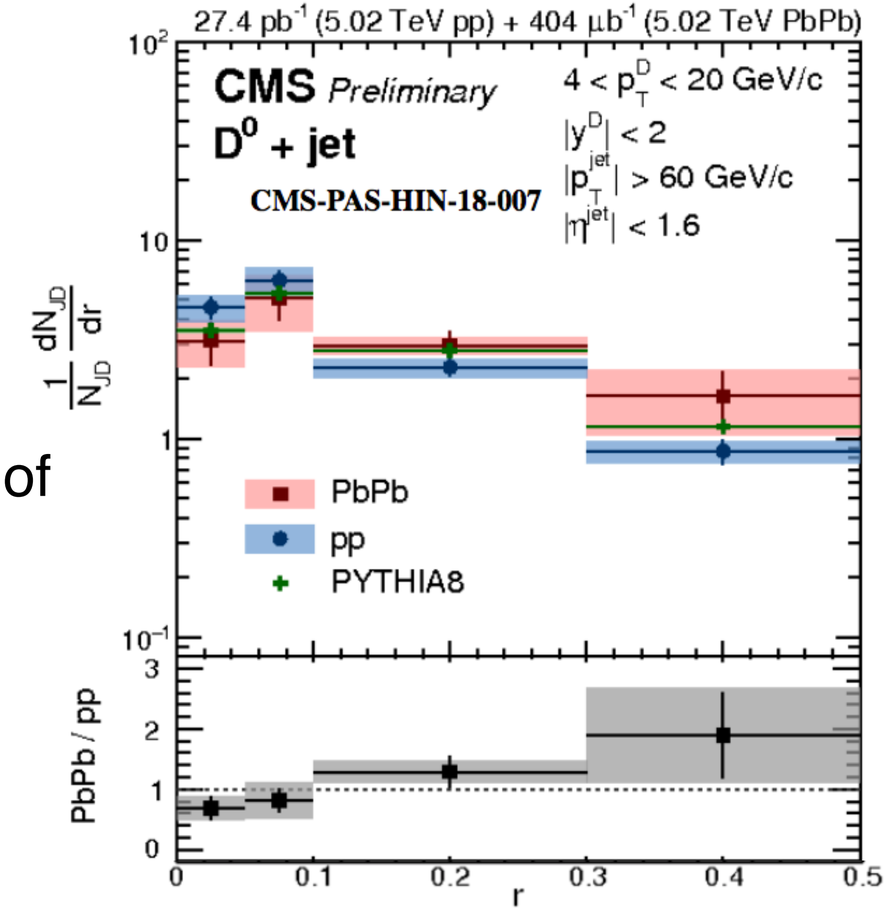
- Hint of less suppression of b—>e compared to c—>e at RHIC
- Less suppression of B hadrons than D hadrons at LHC

Heavy flavor jets at LHC





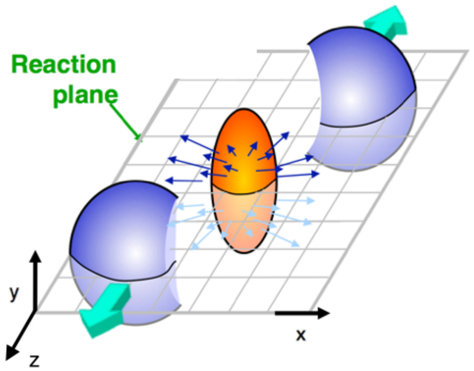
- Does distribution of HQ within jets change in QGP?



- R_{AA} of D^0 tagged jets, consistent with that of D^0
- Modifications in fragmentation not a large effect for D^0 R_{AA}

- Hints of modification of D^0 - jet correlations in QGP

Elliptic flow of charm mesons

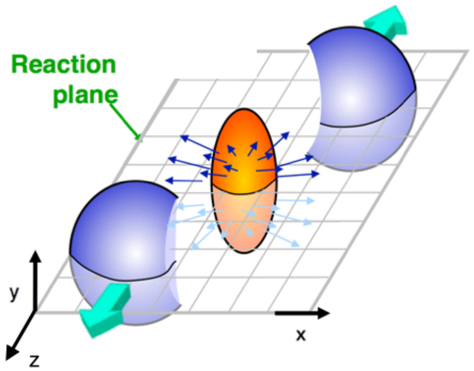


$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n).$$

Collective expansion of QGP medium

HQ acquire flow as they transport through and interact with QGP

Elliptic flow of charm mesons



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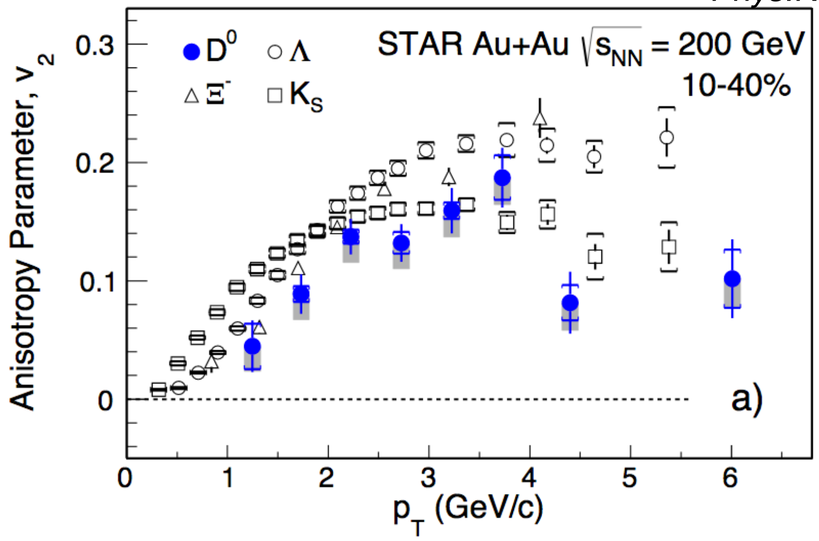
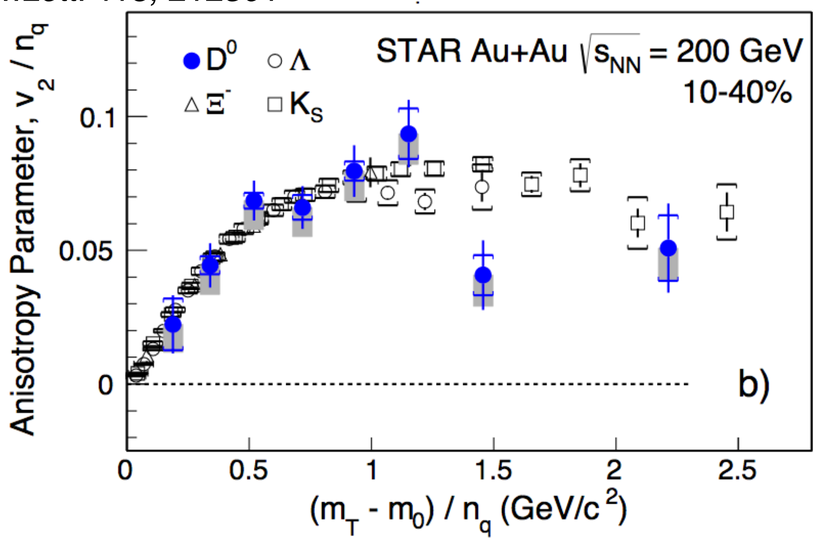
Phys.Rev.Lett. 118, 212301

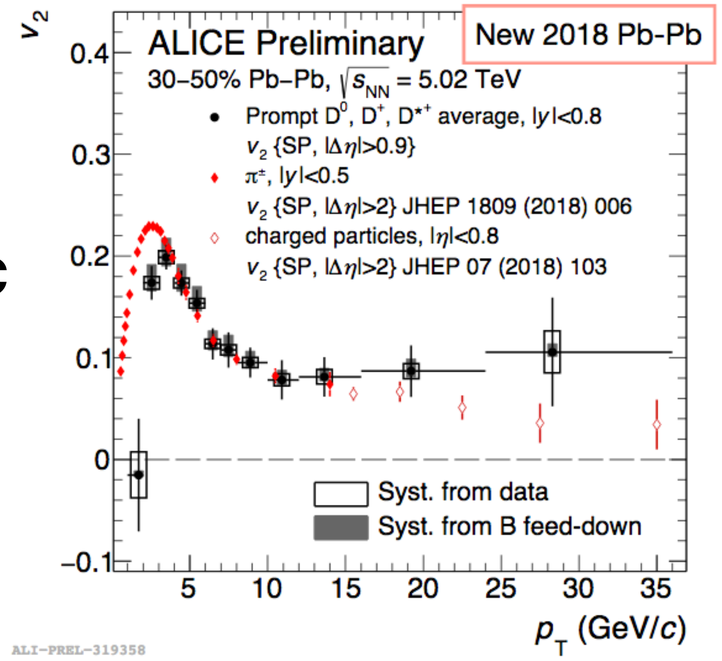
RHIC





Constituent Quark scaling

LHC

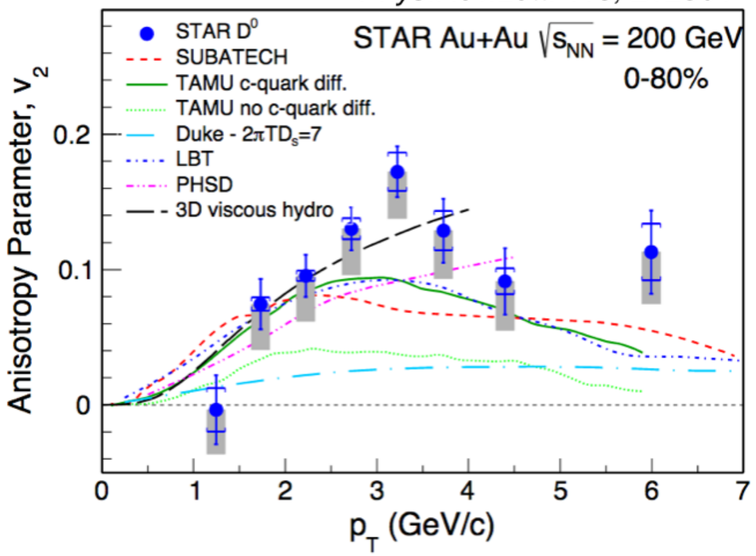


- Large elliptic flow values for D mesons, comparable to that of light hadrons
- Follows NCQ scaling - suggests charm quarks flow along with QGP

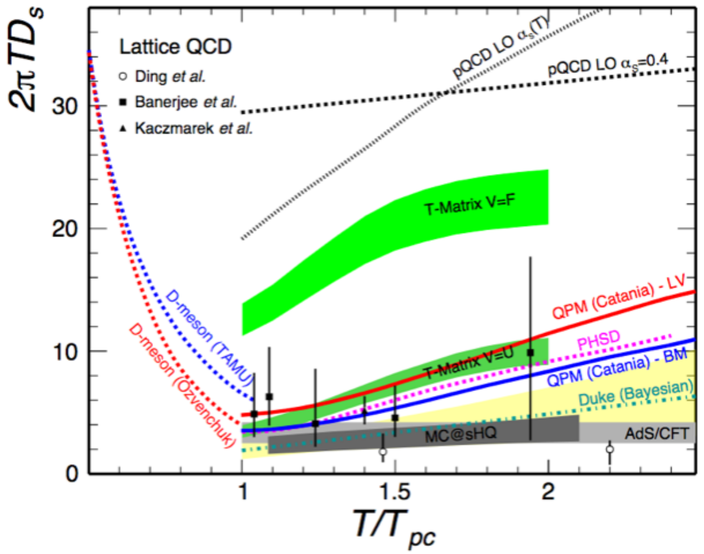
Elliptic flow of charm mesons

- Also can constrain the charm quark diffusion coefficient in QGP
- Small values of $2\pi TD_s$, well constrained by data ~ $T = T_c$

Phys.Rev.Lett. 118, 212301



arXiv:1903.07709



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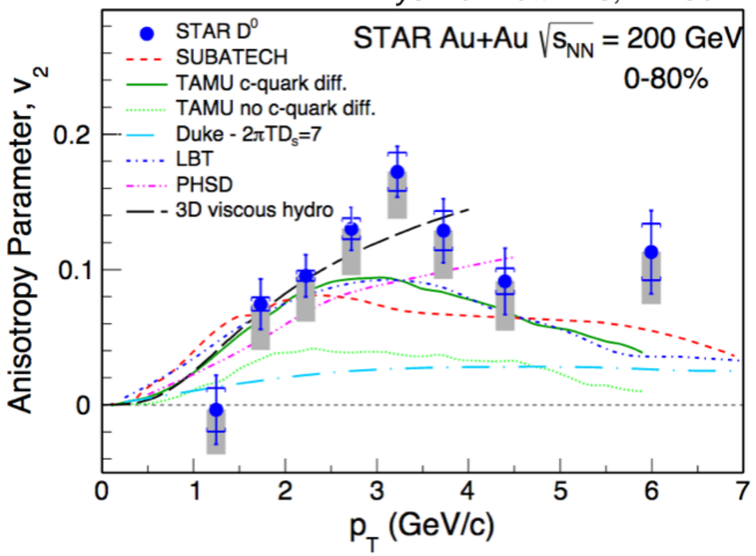

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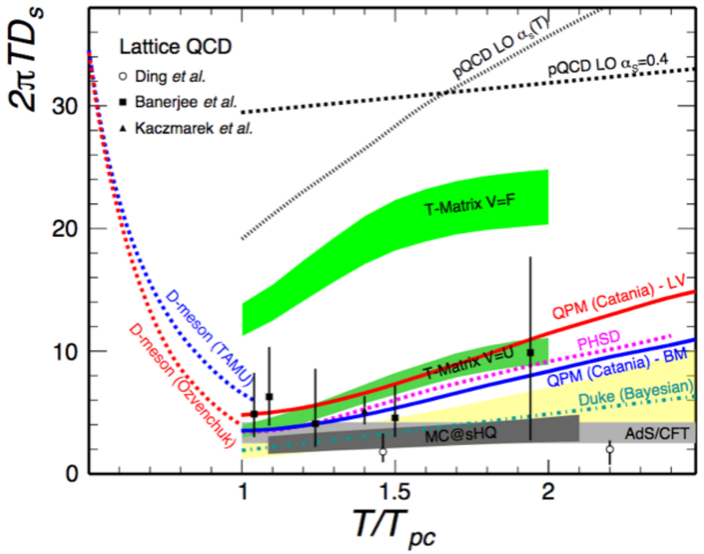

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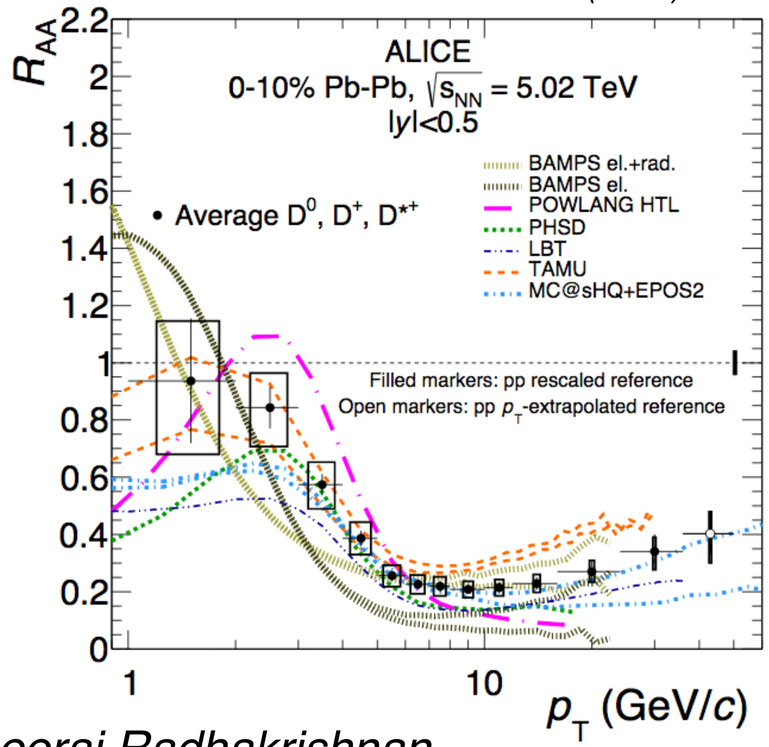
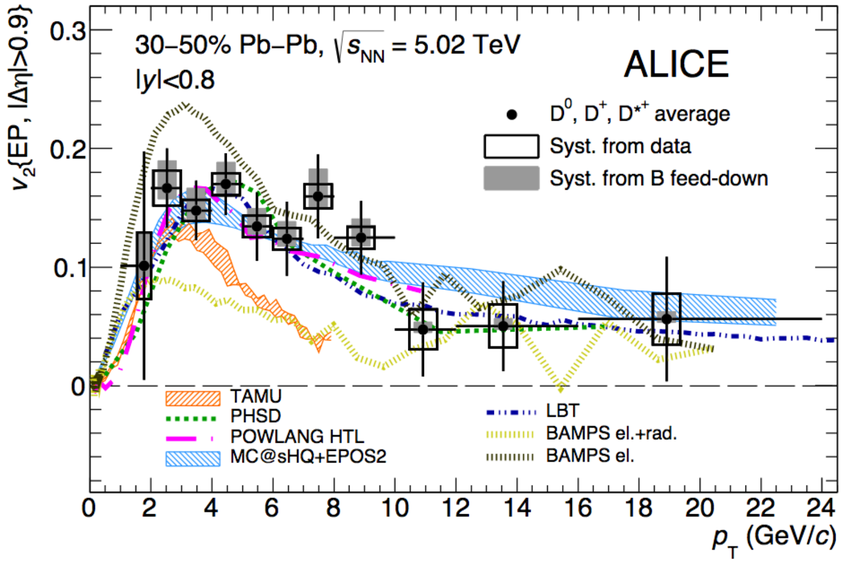


JHEP 1810 (2018) 174



- Simultaneous description of v_2 and R_{AA} helps better separate between the models

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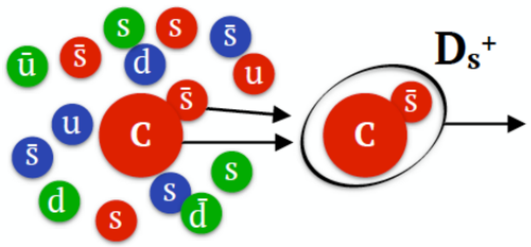
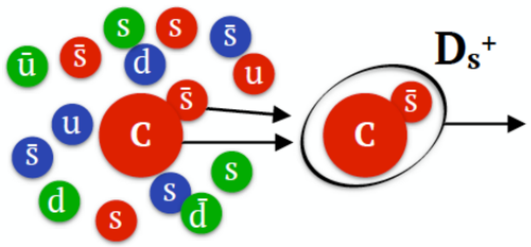
Hadronization - D_s production



- Hadronization via coalescence can be important in the presence of QGP
- Enhanced strangess in QGP + coalescence hadronization —> D_s enhancement

Hadronization - D_s production



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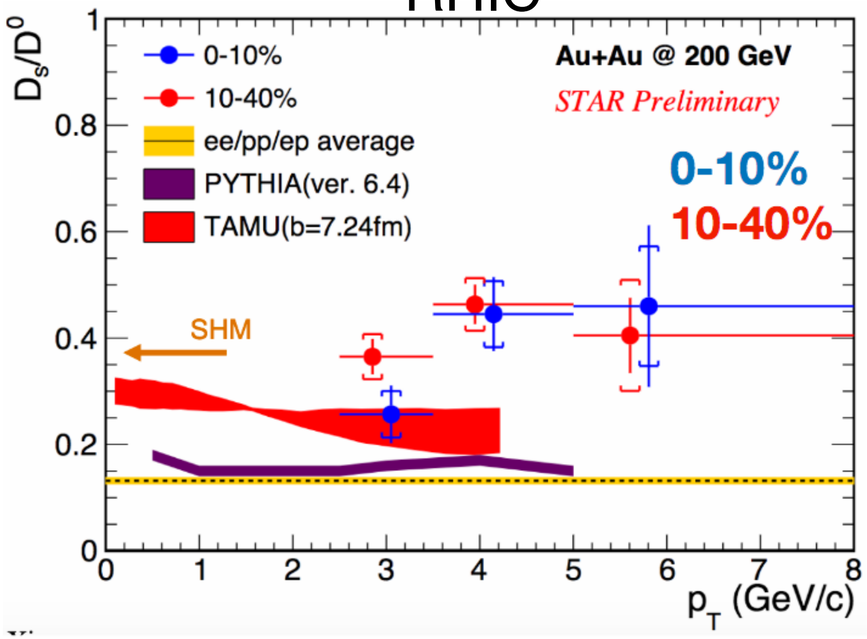
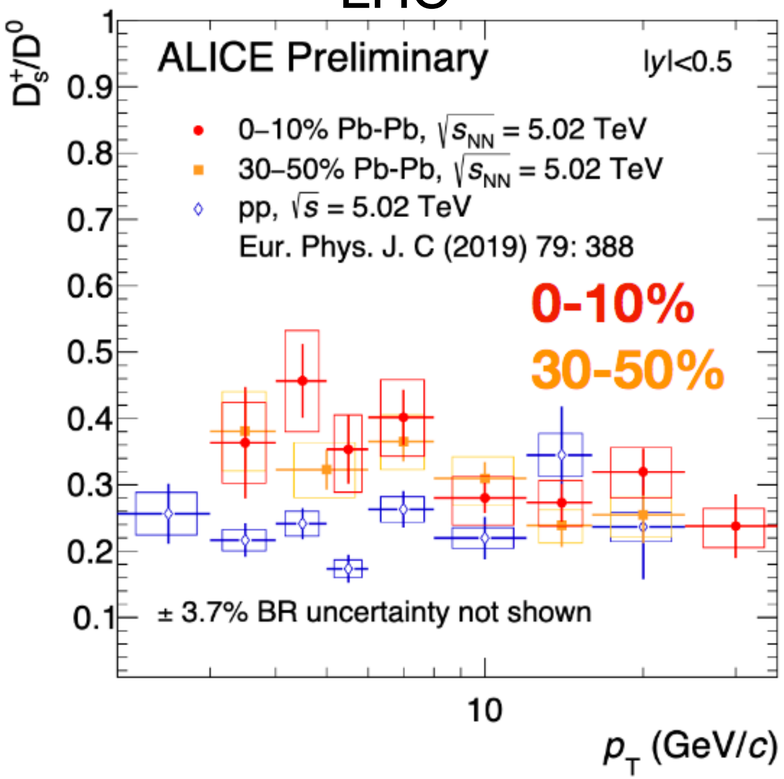
RHIC

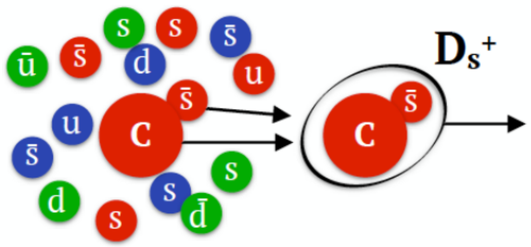


LHC



- D_s/D^0 ratio higher in A+A compared to p+p and e+e,e+p
- Enhancement predicted by coalescence model calculations, but underpredicts data at RHIC

Hadronization - D_s and B_s production



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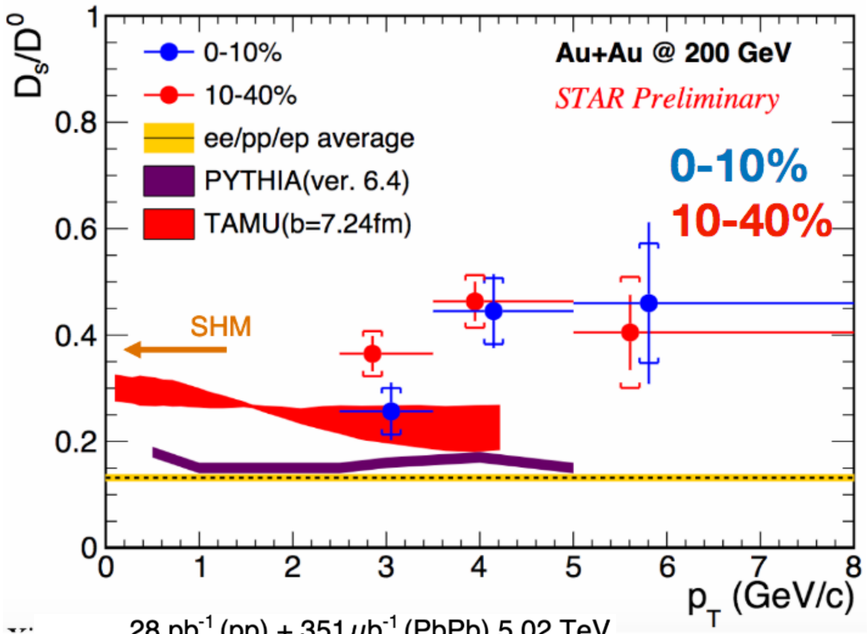

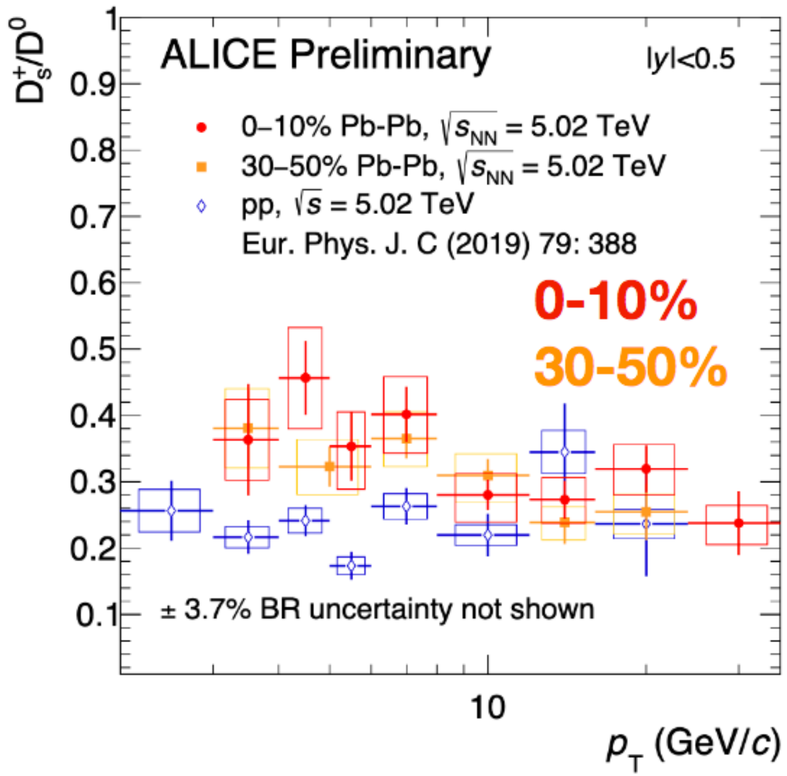

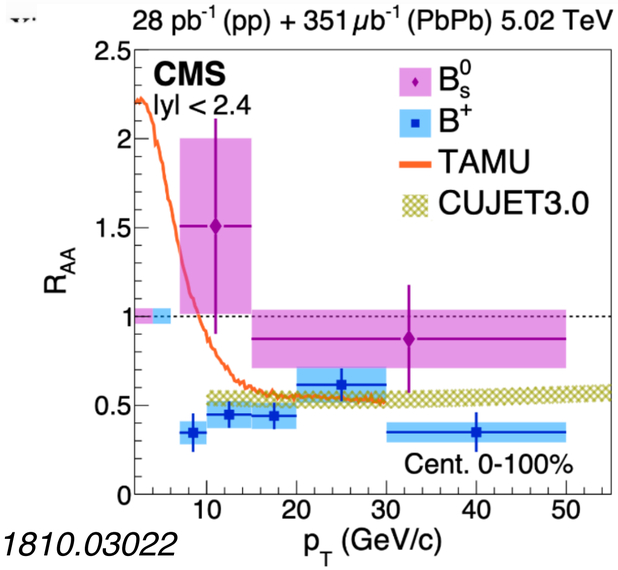

arXiv:1810.03022

- Hint of enhancement also for B_s production at LHC

Baryon production - Λ_c

- Baryon/meson ratio at low p_T valuable tool to study hadronization

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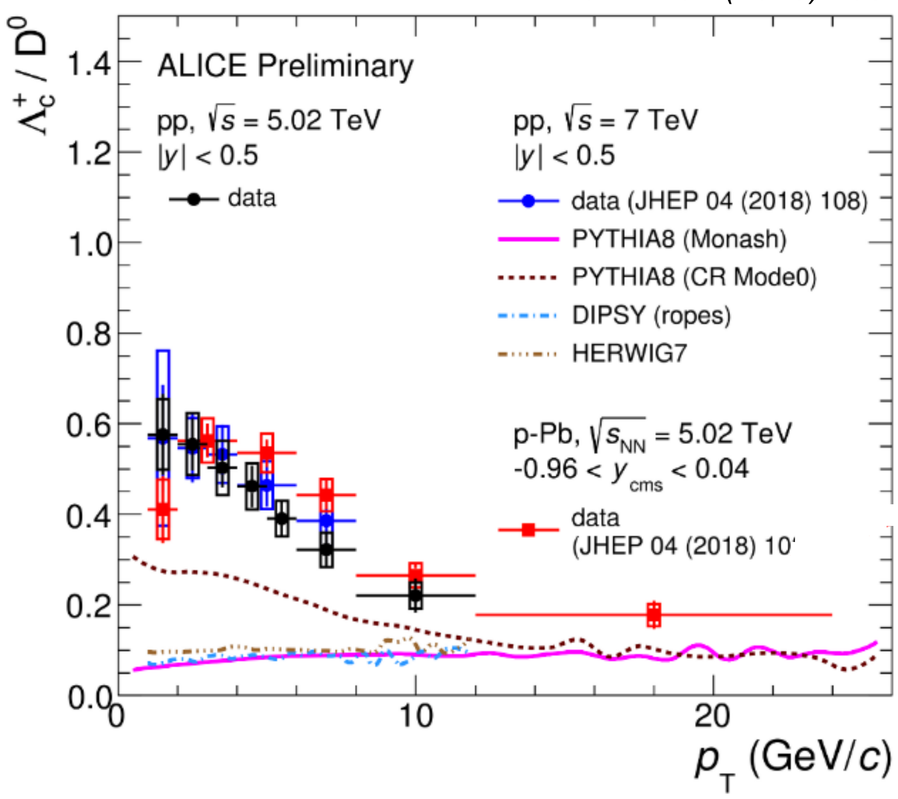


- Strong enhancement of Λ_c production in p+p and p+Pb collisions compared to fragmentation ratios measured at high p_T

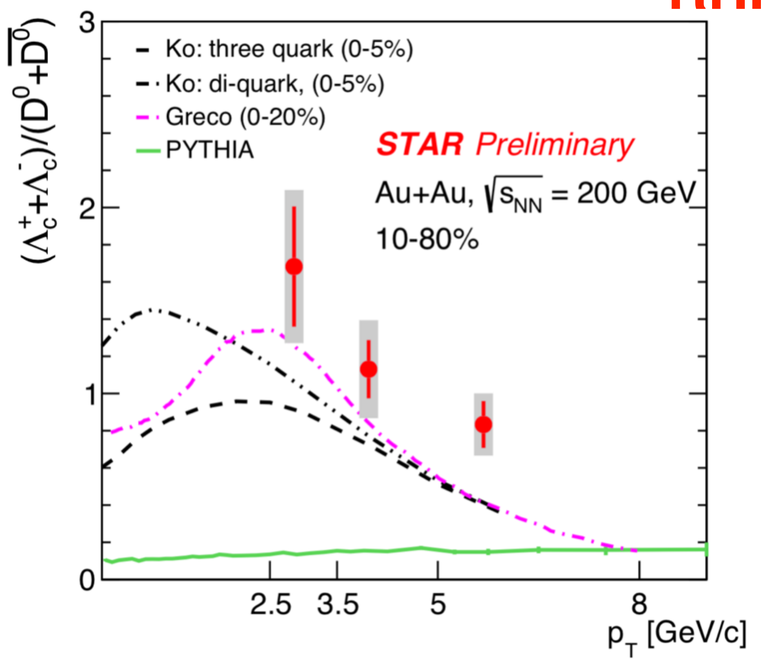
- PYTHIA with CR also underprdict Λ_c production

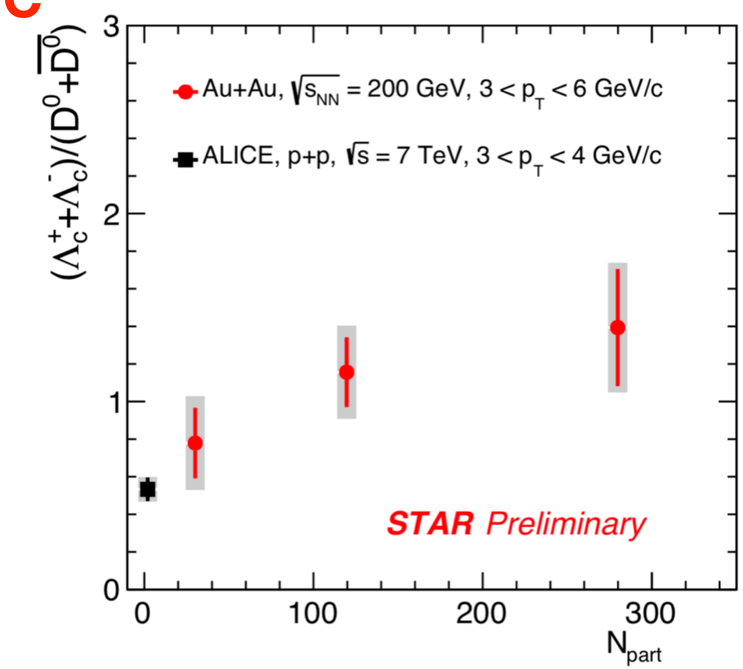
- How does charm baryon production evolve in heavy-ion collisions?

Baryon production - Λ_c

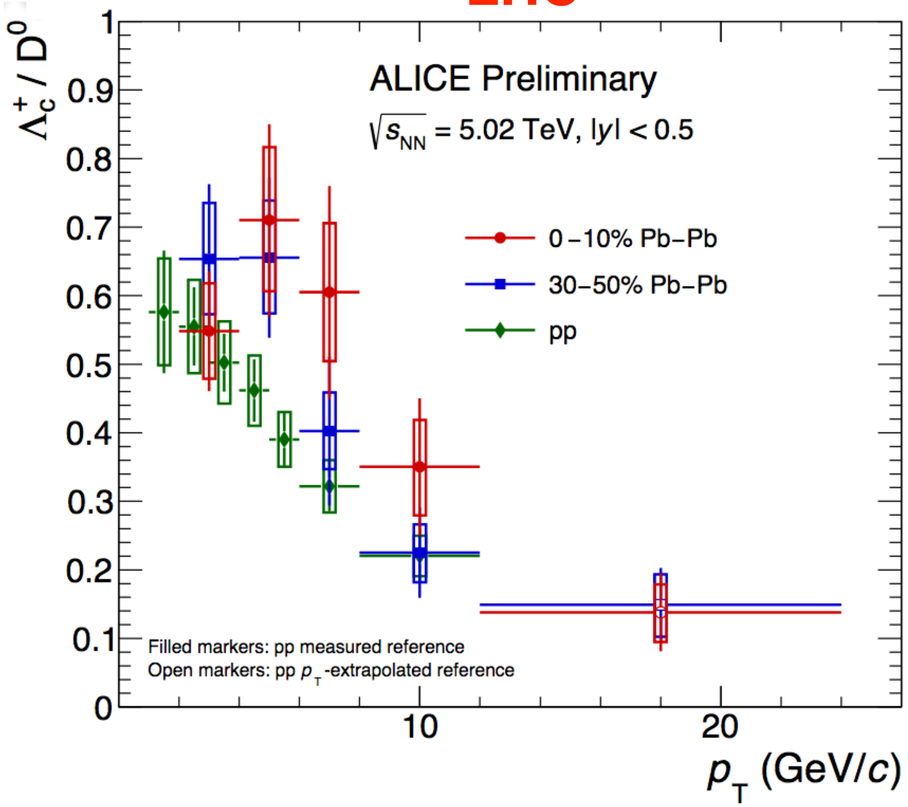
- Coalescence hadronization can produce further enhancement in A+A collisions

RHIC





LHC



- Strong enhancement in A+A collisions compared to vaccum fragmentation values
- Coalescence model calculations are closer to data
- Enhacement higher than in p+p collisions

- Enhancement seen at RHIC larger than at LHC

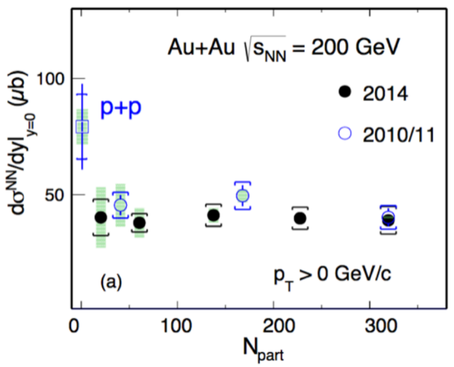
Total charm cross section at RHIC

- Hadron yield ratios change, how about the total charm cross-section?
  - D^0 yields are measured down to zero p_T
  - For $D^{+/-}$, and D_s, Levy (power law) fits to measured spectra are used for extrapolation (systematics)
  - For Λ_c, three model fits to data are used and differences are included in systematics

per nucleon-nucleon collision

Charm Hadron		Cross Section dσ/dy (μb)
AuAu 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28 *
	Total	**152 ± 13 ± 29**
pp 200 GeV	**Total**	**130 ± 30 ± 26**

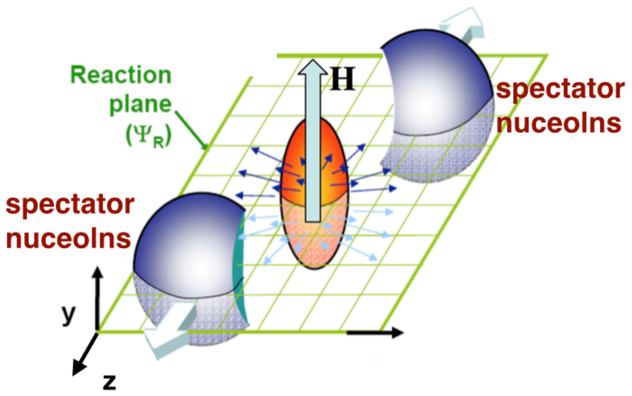
*** derived using Λ_c^+ / D^0 ratio in 10-80%**

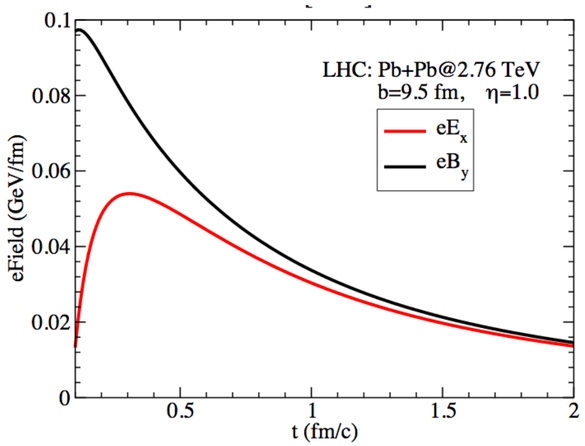


- Suppression of D^0, enhancement of D_s and Λ_c

- Total charm cross-section consistent with p_T within uncertainties

HQ as probes of initial conditions



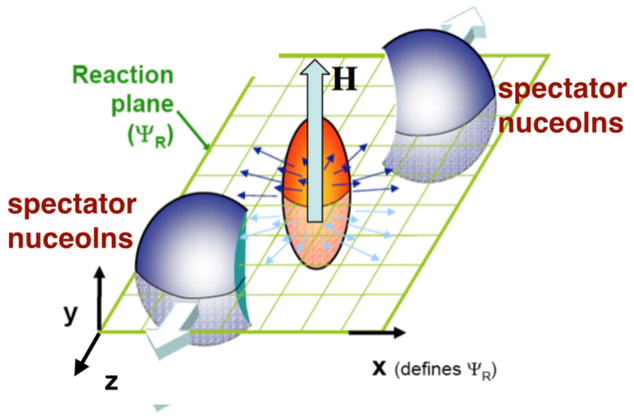


- **Very strong EM fields at initial stages in HIC**

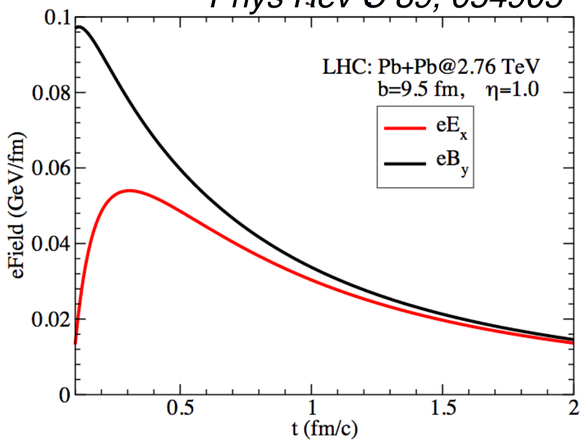
HQ as probes of initial conditions

- HQ produced predominantly in initial hard scatterings
- Larger relaxation times
- Can carry information on initial conditions

- Charge dependent splitting of directed flow, v_1 ($\langle p_x/p_T \rangle$) relative to RP



Phys Rev C 89, 054905



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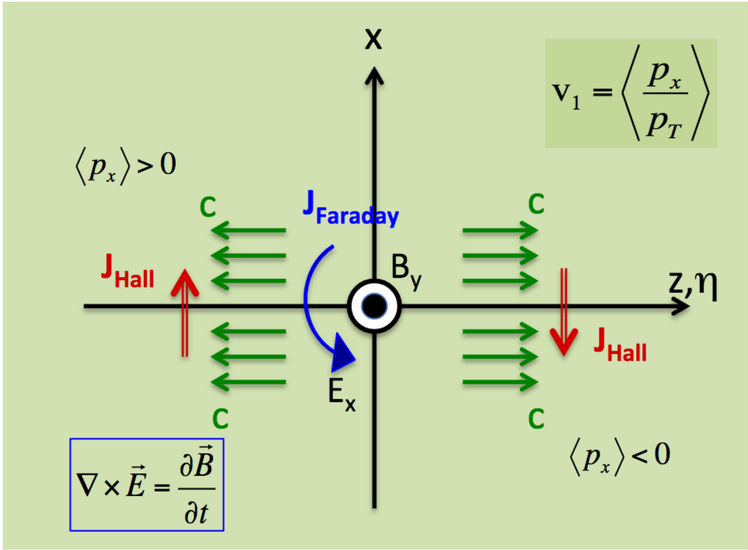
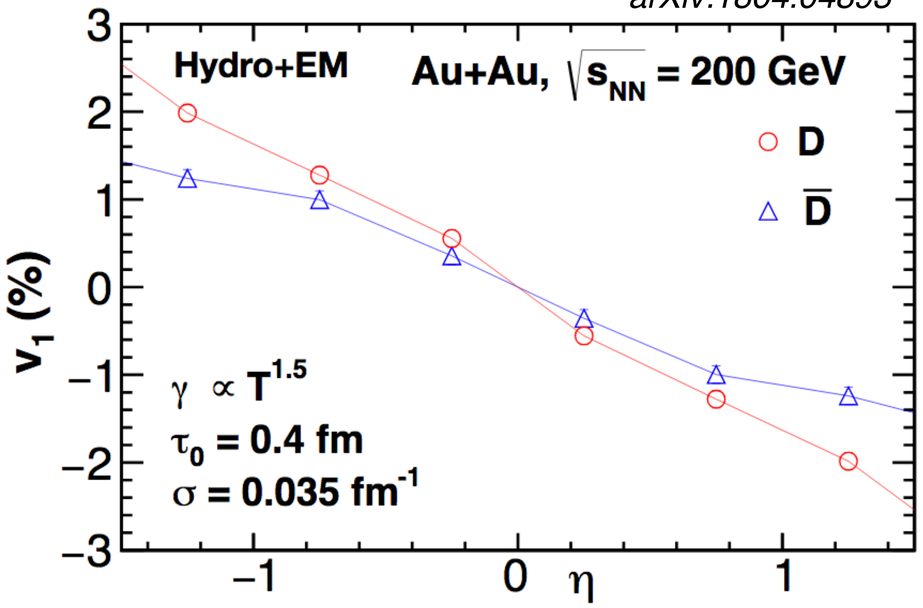
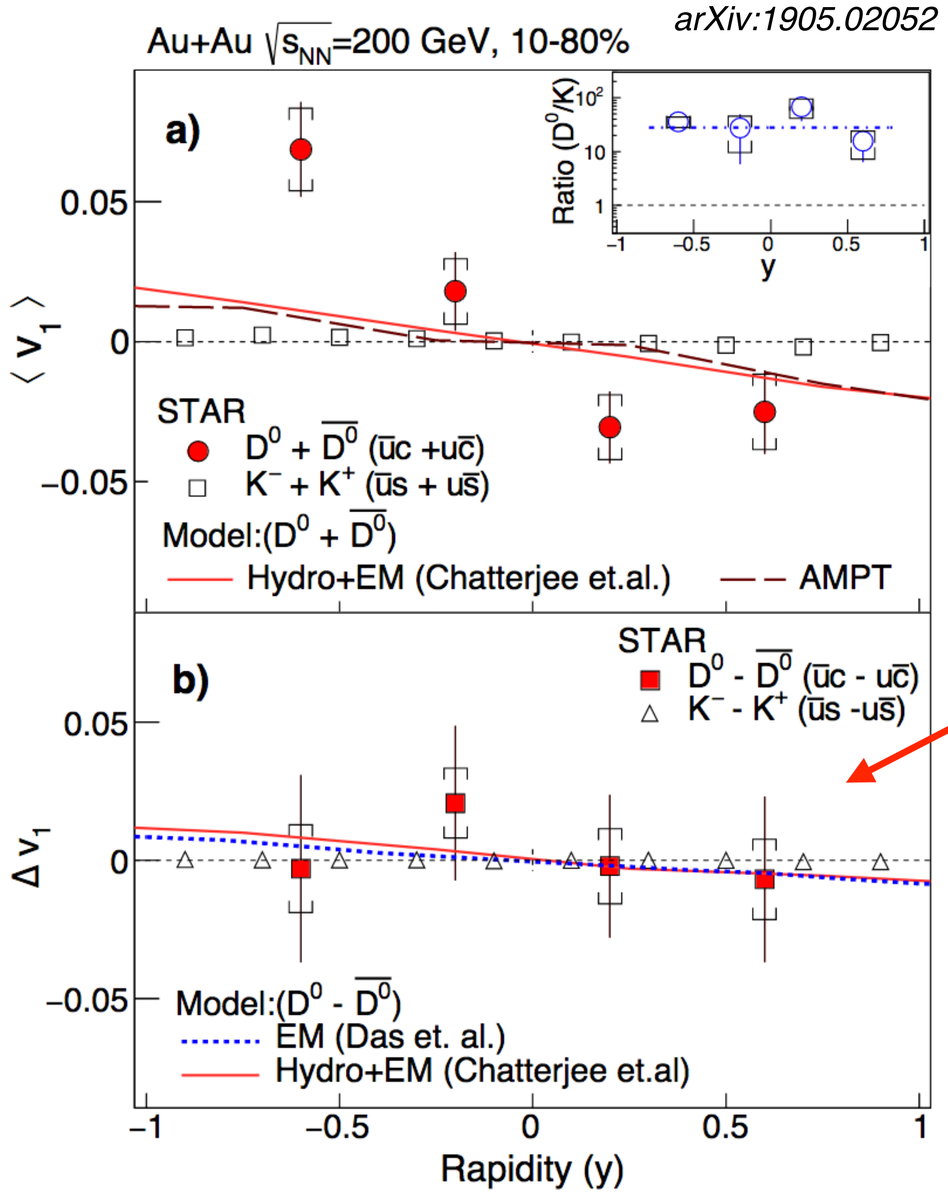


arXiv:1804.04893



- Model calculations predict a few percent difference in v_1 of D^0 and $\overline{D^0}$ after transport through QGP

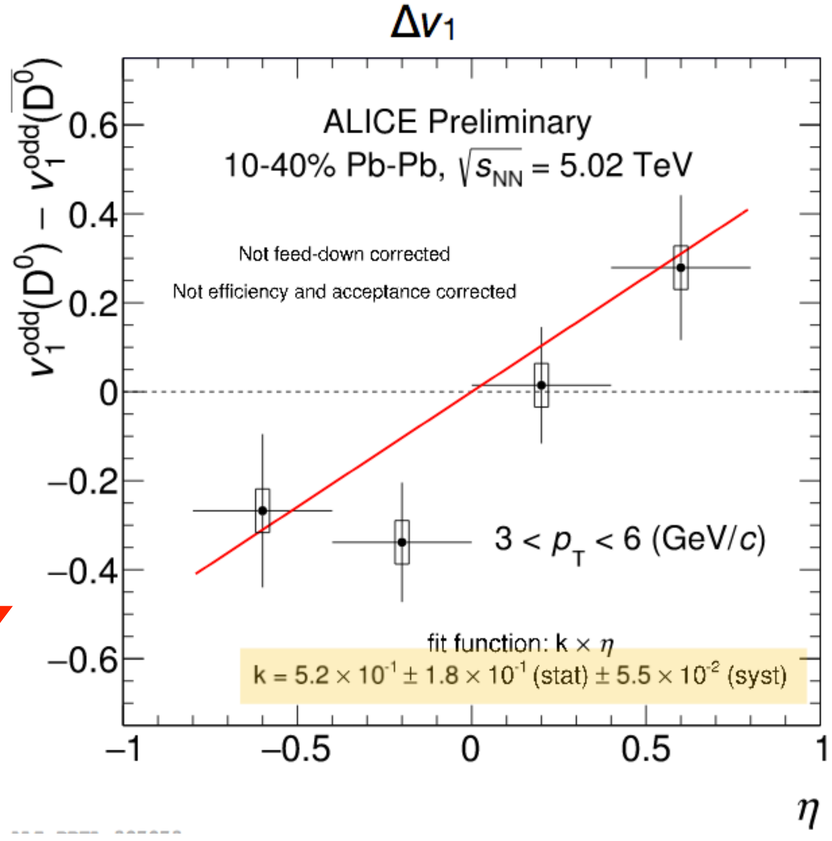
HQ as probes of initial conditions



- **Dominant charge independent contribution from initial geomtry**

- Difference between charges consistent with zero at RHIC

- Non-zero difference seen at LHC



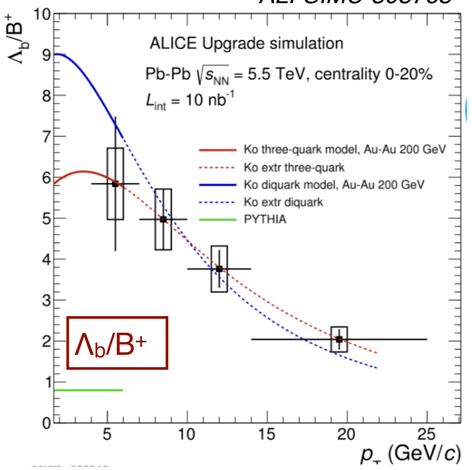
- Need more precision measurements

Summary and Outlook

- **Strong suppression and energy loss of high p_T HF hadrons in HIC**
  - Disentangling enegy loss mechanisms
- **Large elliptic flow values**
  - Together with R_{AA} provides better constrains on HQ interactions in QGP
- **Hadronization mechanism**
  - Modification of hadrochemistry in A+A
  - Importance of coalescence hadronization in heavy-ion collisions
- **HF meson v_1 a potential tool to study the strong initial EM fields**

- **High precision HF measurements major focus at upcoming sPHENIX and LHC Run3**
  - Dedicated high resolution HF tracking systems - ALICE ITS and sPHENIX MVTX
  - Expected integrated luminosity of 10^{-1} nb (13^{-1} μb existing) at ALICE and 240 Billion MB events (2B existing) at sPHENIX

ALI-SIMU-308768



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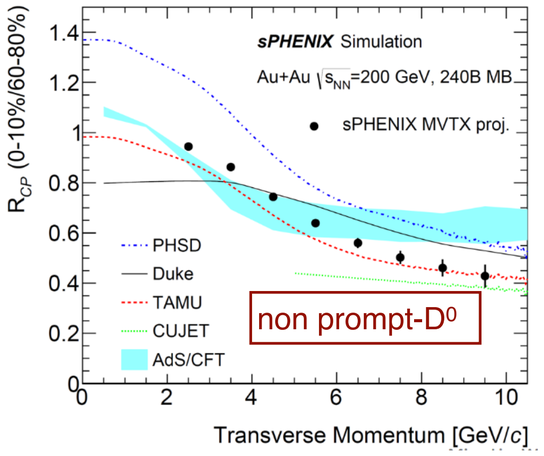
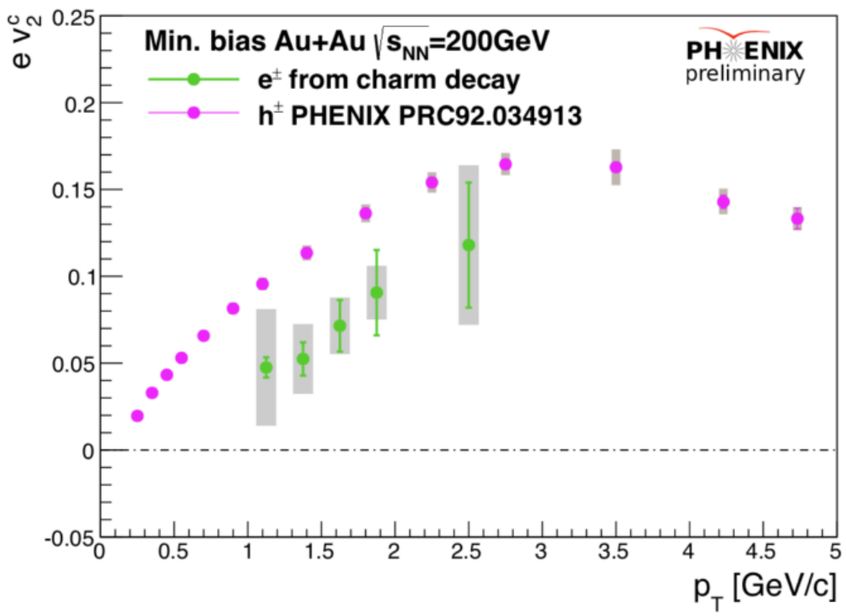
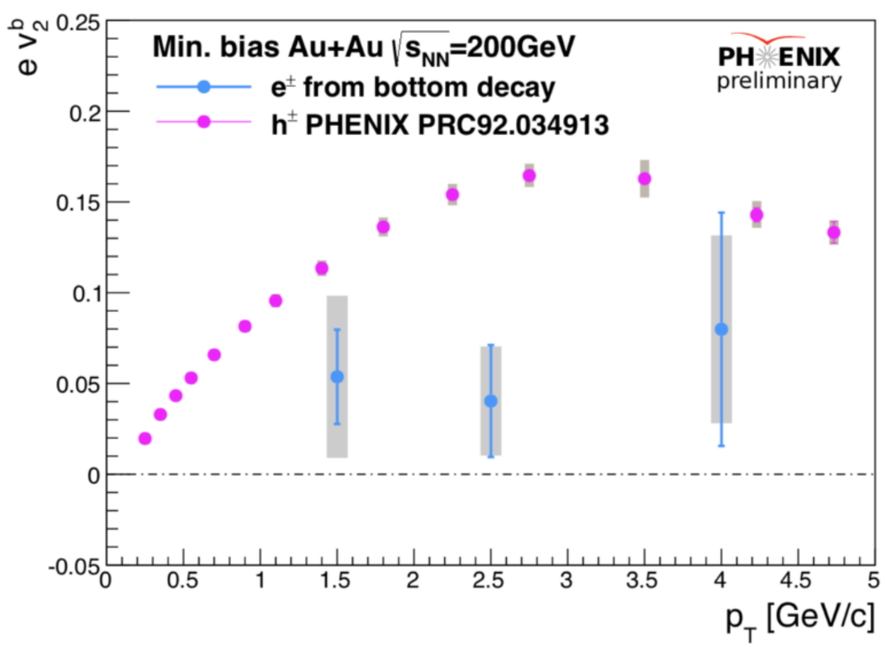


THANK YOU!!

Back up

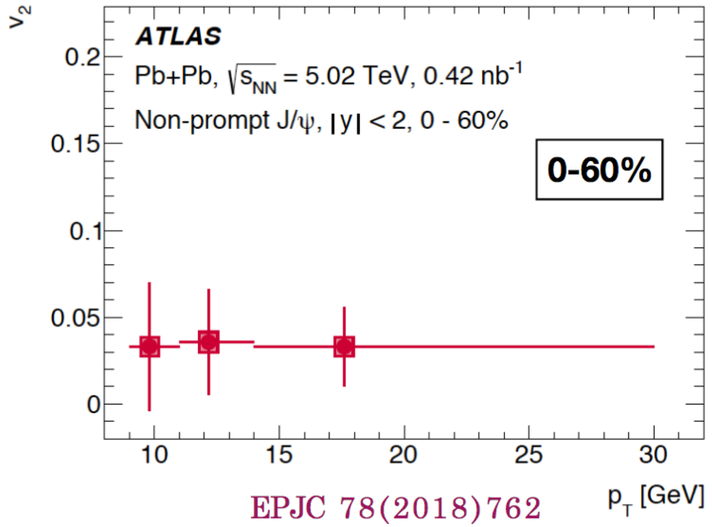
Bottom flow?



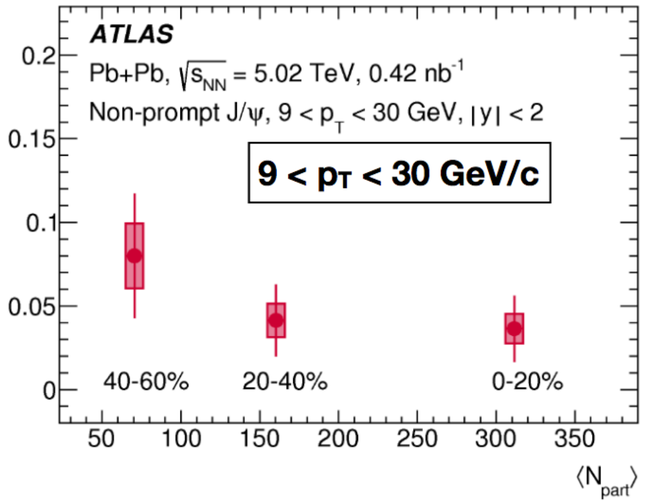


- v_2 of c—> e (left) and b—> e (right), and of non-prompt J/Psi (bottom)

- Early attempts at bottom v_2 measurements
- Suggests smaller values, but limited statistics at present

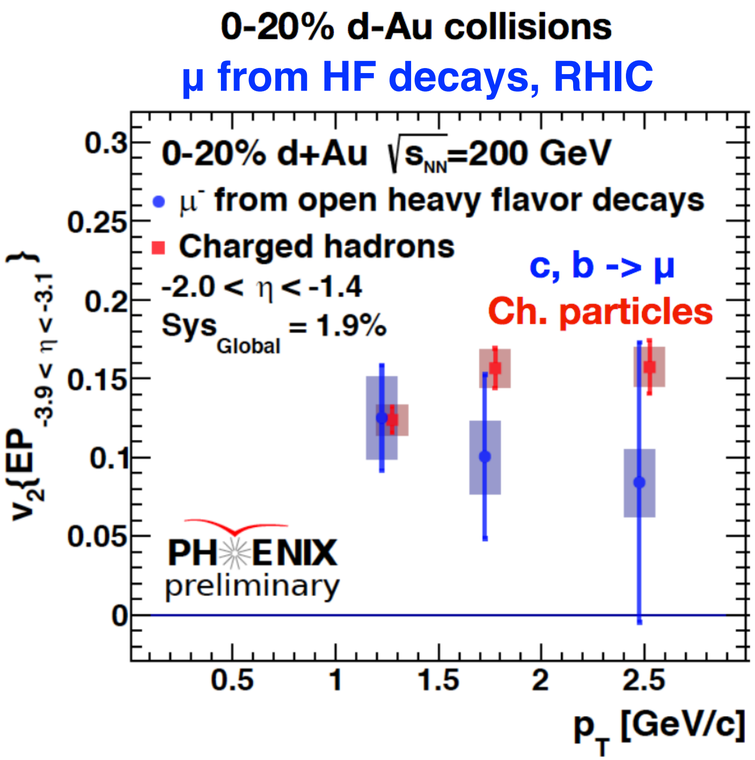


EPJC 78(2018)762



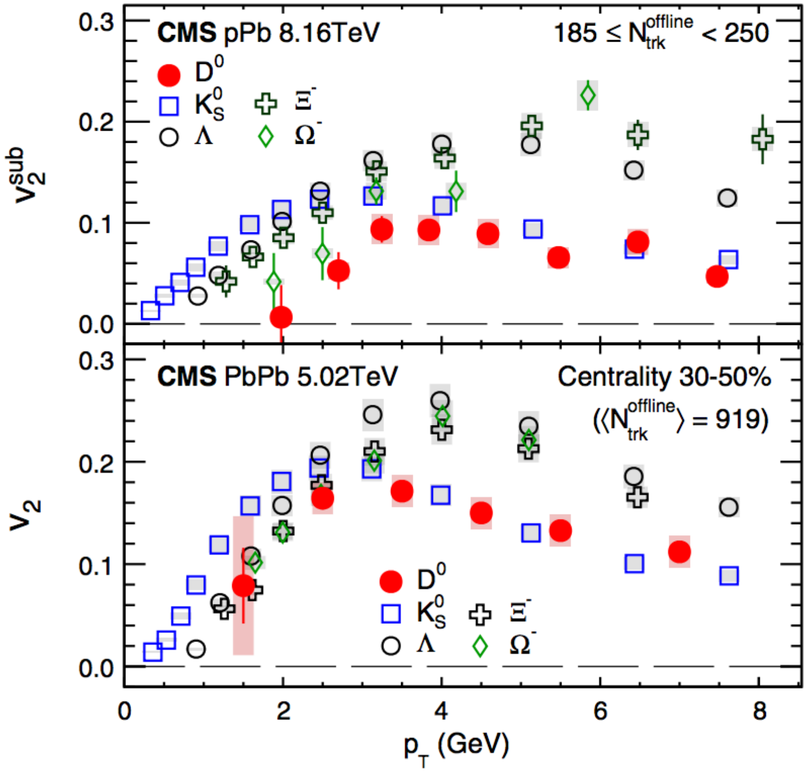
HF v_2 in small systems at high multiplicity

- Small systems at high multiplicty show features of collective expansion!
- Large v_2 also for HF hadrons



Phys.Rev.Lett. 121, 082301

D^0, LHC



- Seen at RHIC and LHC

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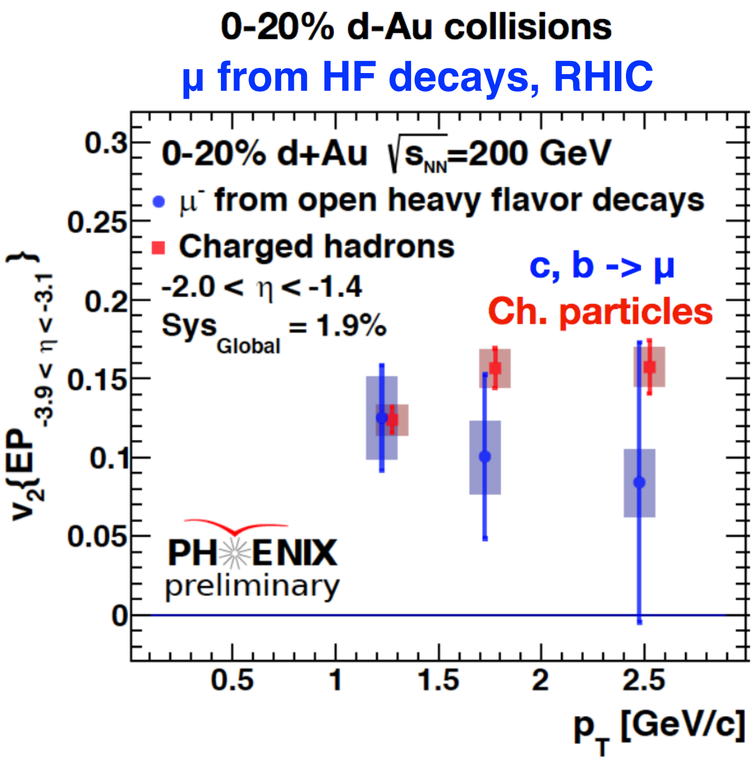

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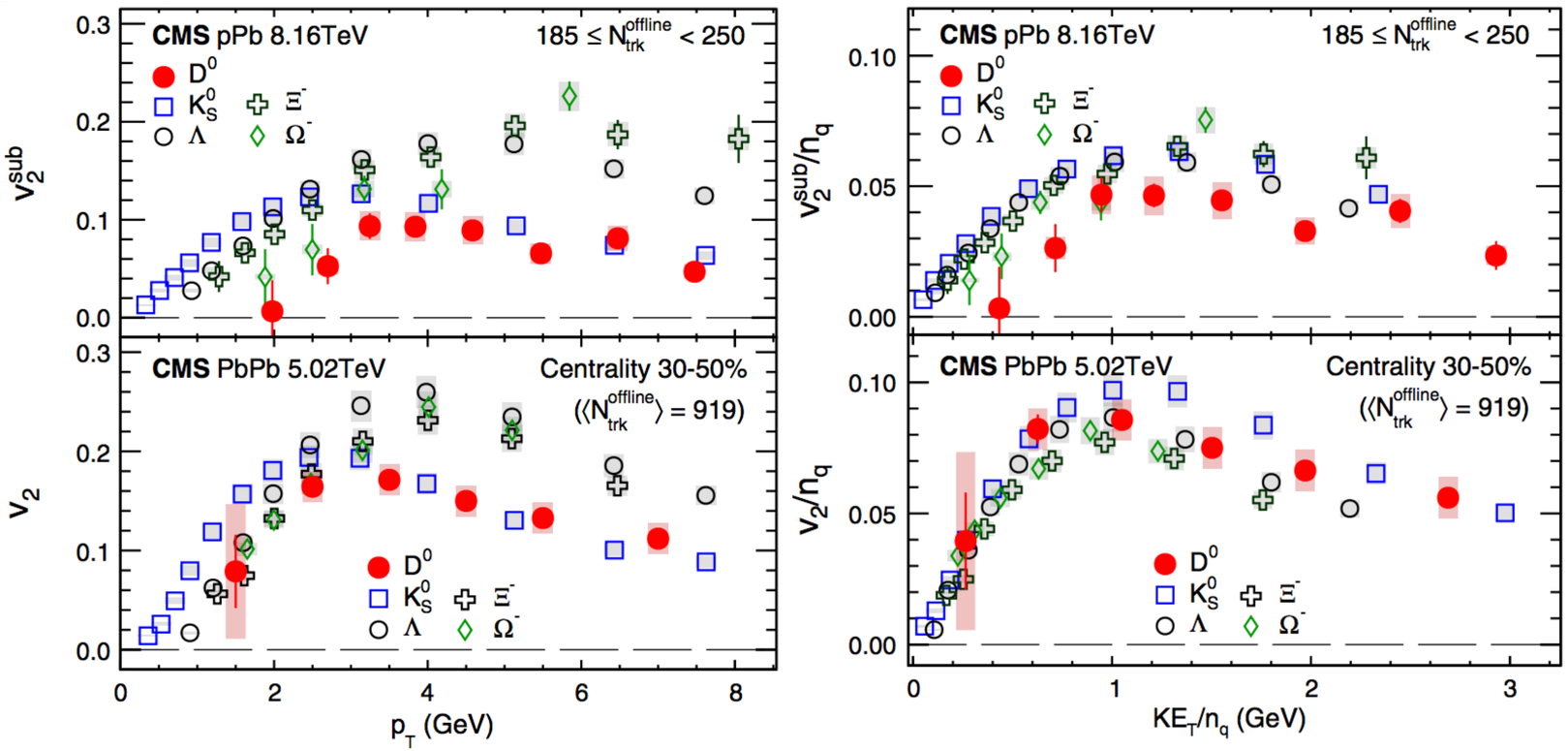
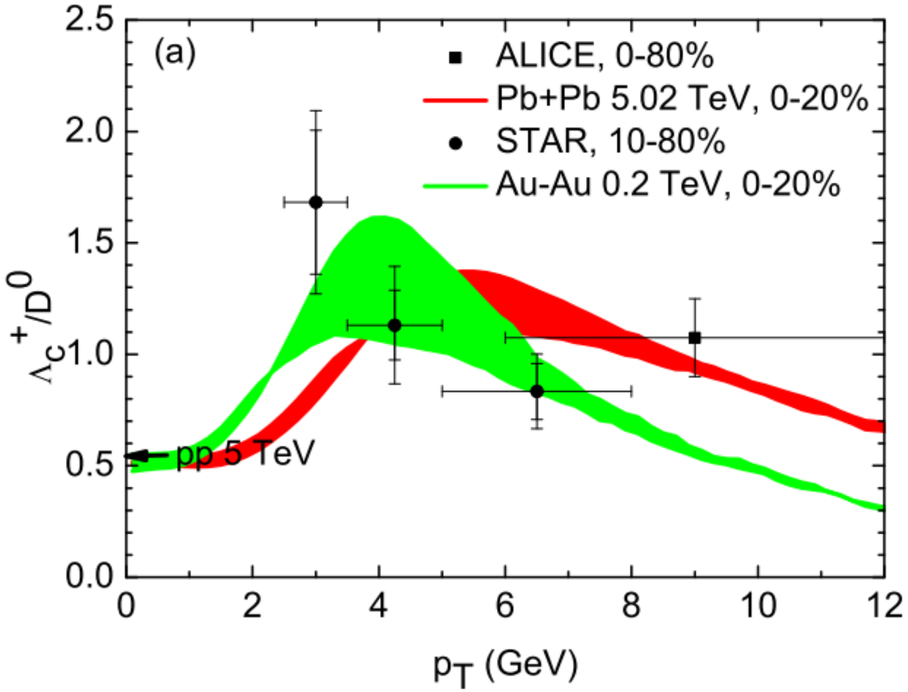
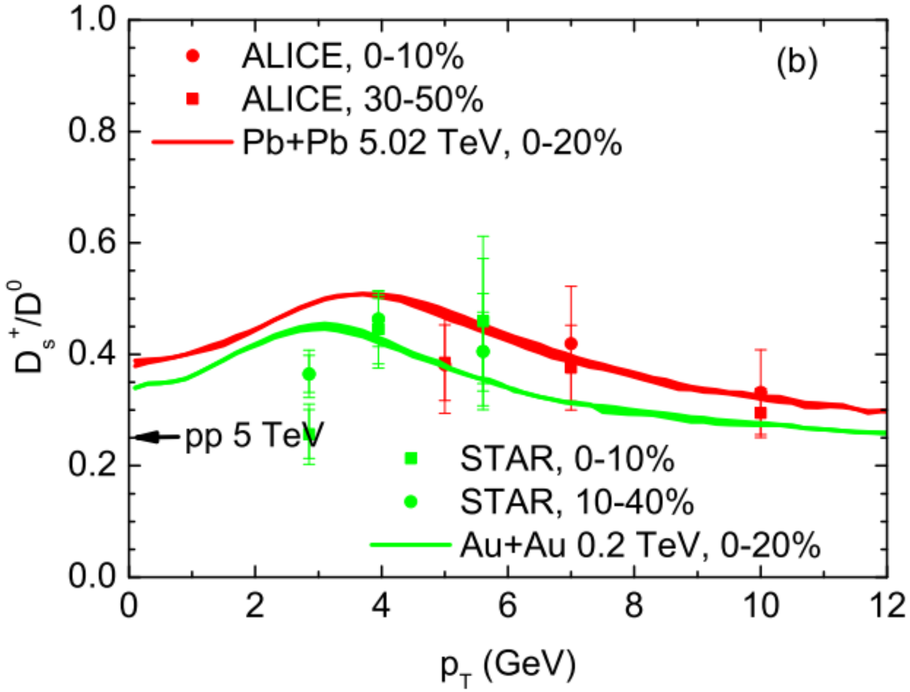


Constituent Quark scaling

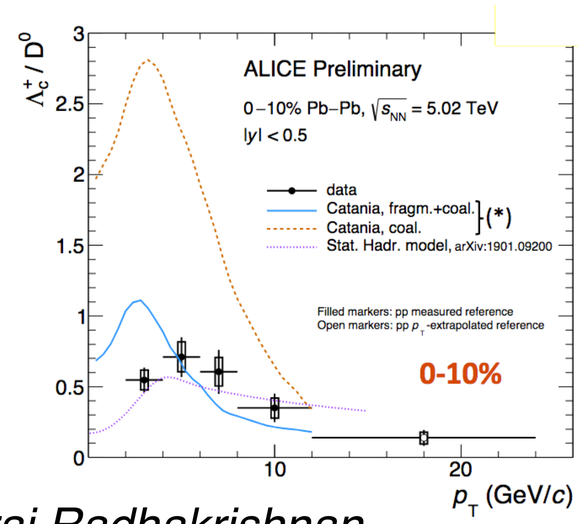
- Smaller v_2 values after NCQ scaling for charm compared to light hadrons in p+Pb

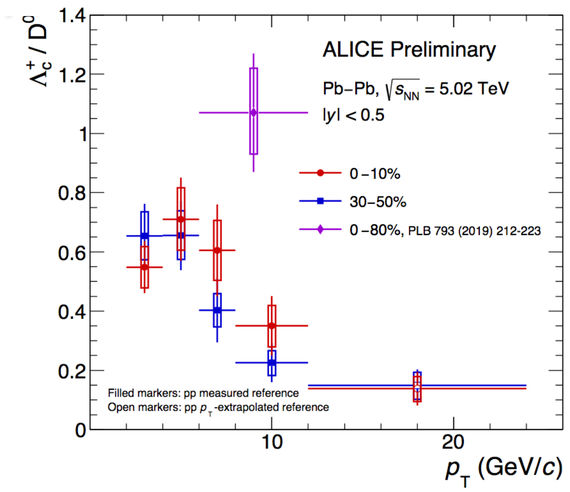
Λ_c/D^0 model comparisons





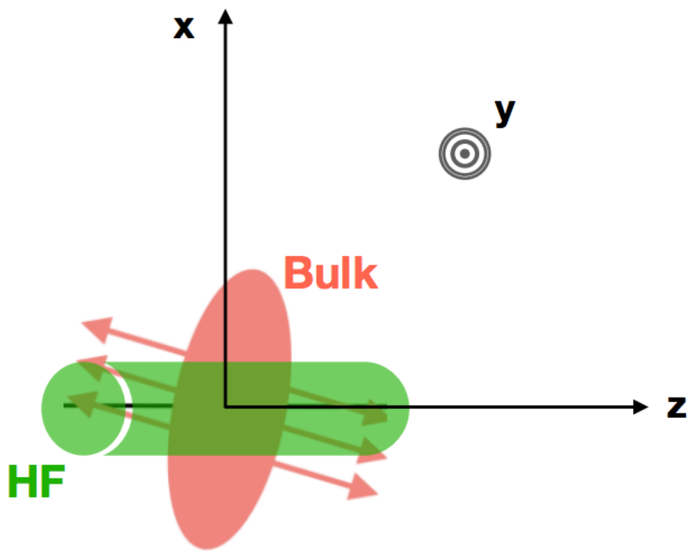
- Peak is shifted to lower p_T at RHIC energies in model calculations





Sooraj Radhakrishnan

D^0 v_1 from initial geometry



- QGP bulk is tilted in Reaction Plane as a function of rapidity
- HQ peoduction profile is symmetric in rapidity
- Causes enhanced initial first order asymmetry in density distributions
- Viscous drag from the expanding bulk medium produces large v_1 for heavy flavor quarks