Open Heavy production & final state interaction(AA,pA)

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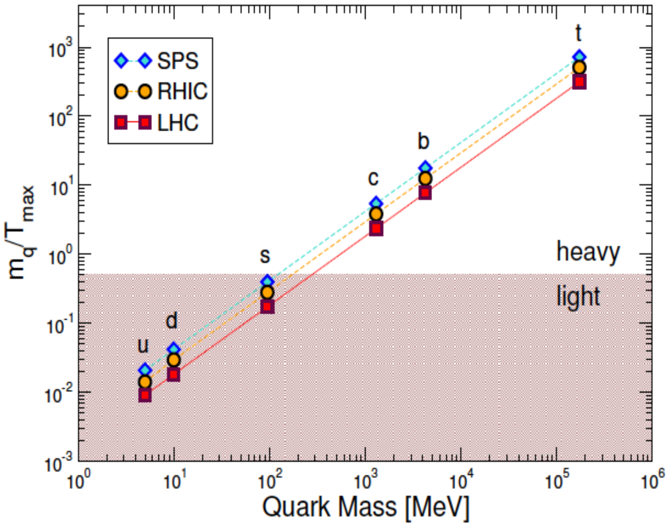
An overview of the transport dynamics and hadronization in AA (pA,pp)

CFNS-EIC 2020, 4th-6th November 2020, Zoom (USA)

Basic Scales



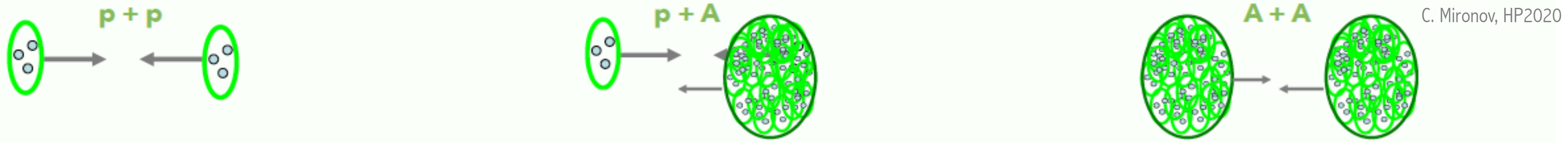
Why Heavy in AA:

- $m_{c,b} >> \Lambda_{QCD}$ pQCD-NNLO initial production
- $m_{c,b} >> T_{RHIC,LHC}$ negligible thermal production (not @FCC)

Specific Features:

- $\tau_0 < 0.08$ fm/c $<< \tau_{QGP}$ witness of all the QGP evolution
- $\tau_{th} \approx \tau_{QGP} >> \tau_{q,g}$ carry more information of their evolution

- $m_{c,b} >> gT_{RHIC,LHC}$ soft scatterings → Brownian motion (low p charm)
- Link to lQCD F(r,T) & space diffusion + NRQCD

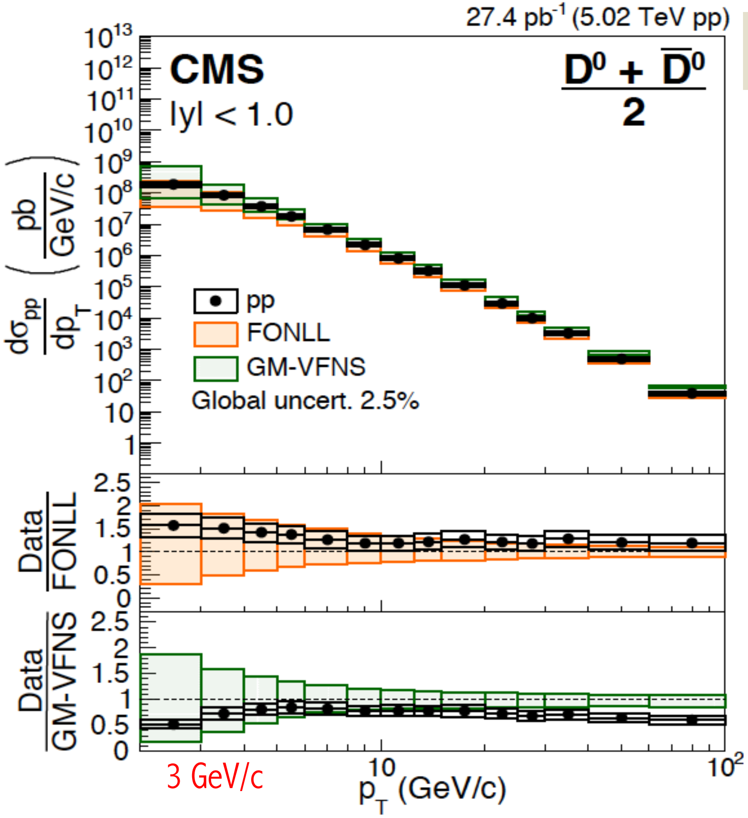


Have a baseline/reference system where production is understood

Nuclear/cold effects are under control

Understand the interactions/hadronization in medium

Open charm in pp@LHC



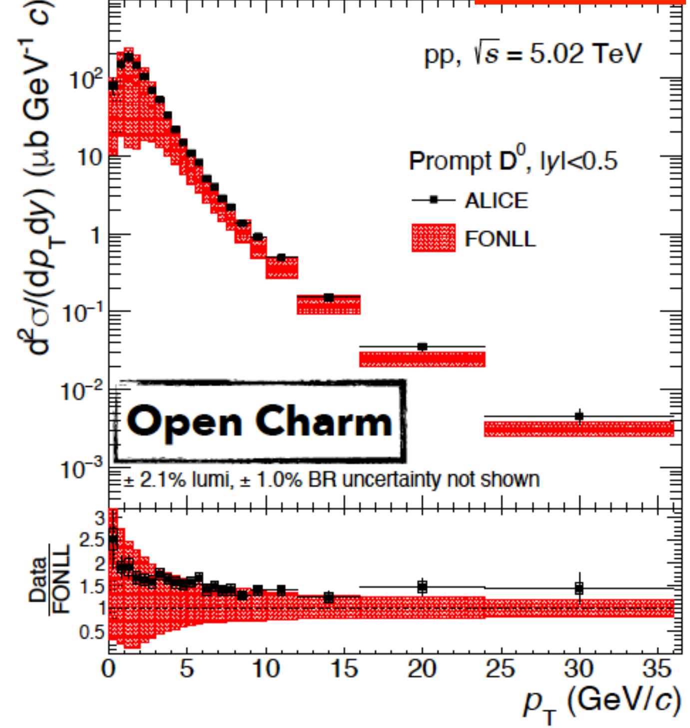
$m_{c,b} >> \Lambda_{QCD}$

$$d\sigma^{Q+X} \simeq \sum_{i,j} f_i^A \otimes f_j^B \otimes d\tilde{\sigma}_{ij\to Q+X}$$

$$d\sigma^H = d\sigma^Q \otimes D_Q^H(z)$$

Only this year measured down to p→0

New 2020



FONNL (Fixed Order NNLO pQCD)

GM-VFNS (General Mass-Variable Fixed Flavor Number Scheme)

Link to lattice QCD

❖ **<u>Extract the Free Energy of QQ</u>**

→HQ Potential F=U-TS

$$q_0^2 \approx \vec{q}^4 / m_Q^2 << \vec{q}^2$$

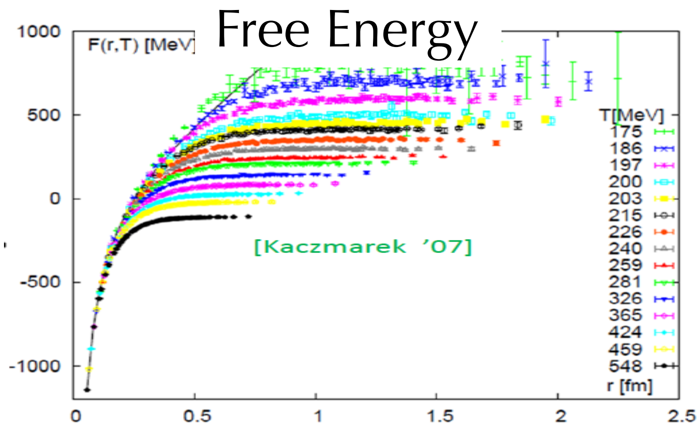
space-like transf. mom. → V(r)

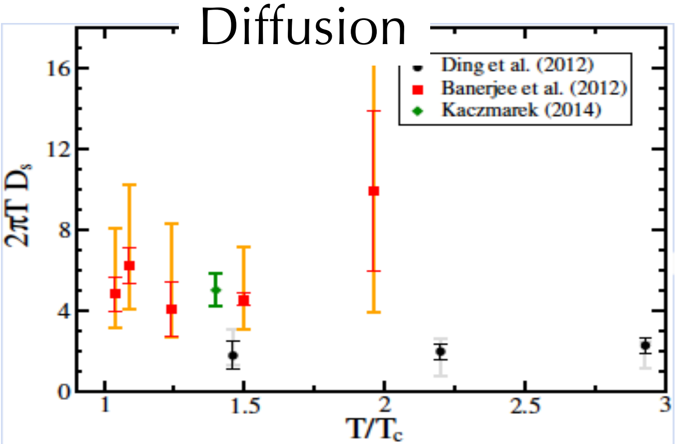
❖ **<u>Evaluate Diffusion Transp. Coeff.</u>**

Extract Spectral function ρ_E from color-electric correlator with an initial assumption for ρ_E, then Kubo formula:

$$\kappa/T^3 = \lim_{\omega \to 0} \frac{2T\rho_E(\omega)}{\omega} \qquad D = \frac{2T^2}{\kappa}$$

<u>Approximations/limitations:</u>
quenched QCD, heavy quark vs. charm quark, continuum extrapolation, …





Outline

✧ Heavy Flavor dynamical evolution in Hot QCD Matter (AA collisions):

- Collisional Energy loss → $D_s(T)$ transport coefficient [p_T<5 GeV] [**non-perturbative**]
- Radiative energy loss and jets [p_T>10 GeV] [**pQCD**]
- Parton Energy loss + FF in-medium cold matter: baseline for EIC

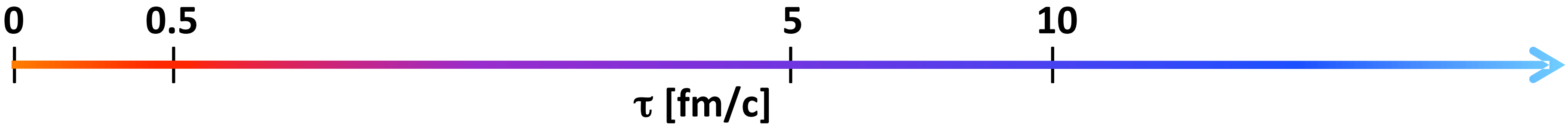
✧ Heavy Flavor hadronization:

- $\Lambda_c/D \approx O(1)$ against FF prediction, PYTHIA and e^+e^-, ep & pp@LHC at forward rapidity
- In-medium hadronization already in pp, pA: **coalescence + fragmentation,** Color Recon
- under current activity@RHIC & LHC (breaking universality of FFs)

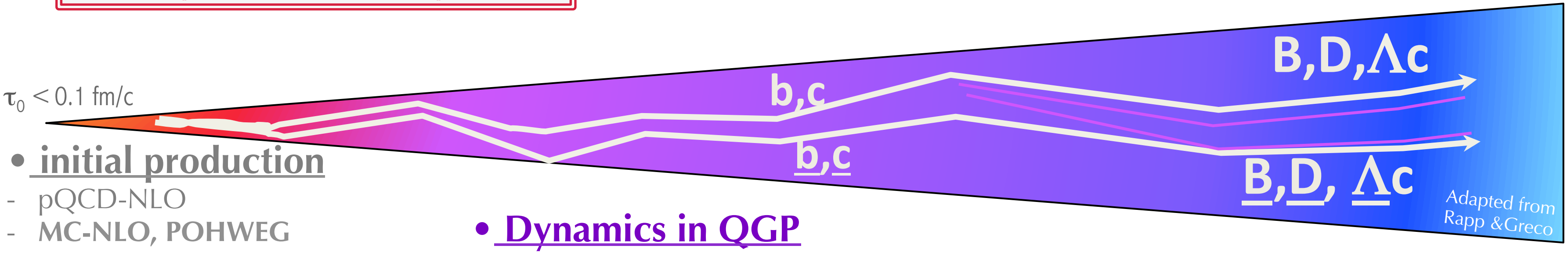
✧ Heavy Flavor as a probe of initial stage:

- impact of Glasma dynamics in pA and AA

Studying the HF in uRHIC

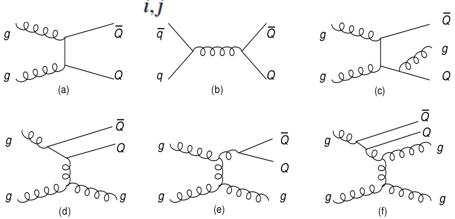


❖ Impact of Glasma phase?!



- **initial production**
  - pQCD-NLO
  - **MC-NLO, POHWEG**
  - CNM effect [pA]

$$d\sigma^{Q+X} \simeq \sum_{i,j} f_i^A \otimes f_j^B \otimes d\tilde{\sigma}_{ij\to Q+X}$$



Angular correlations

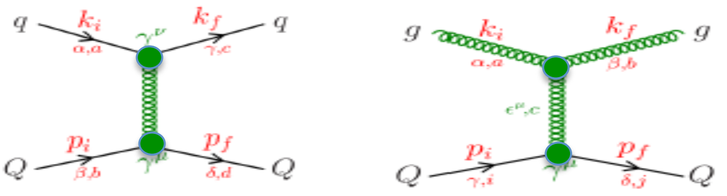
- **Dynamics in QGP**
  - Themalization
  - **Transp. Coeff. of QCD matter D_s(T)**
  - Radiation & Jet Quenching

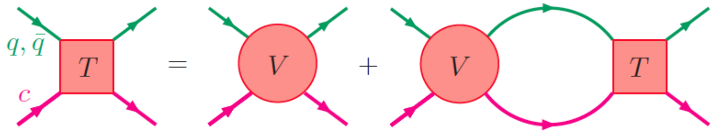
- **Hadronization**
  - coalescence and/or fragm.
  - Λc/D in pp,pA,AA

How HQ interact with the medium

❖ **Elastic Collisional Energy Loss**

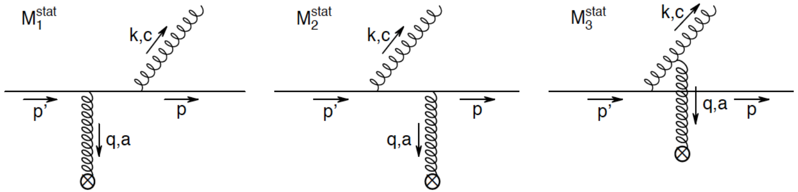
- **pQCD inspired+HTL** (*Torino, Nantes,LBL…*)
  LO diagrams, soft scale resummed in HTL
  infrared singularity, $gT \ll g^2$?
- **QuasiParticleModel** (*Catania, Frankfurt-PHSD*)
  LO diagram, $\alpha_s(T)$ from a fit to lQCD-EoS
  main feature increased strength as T -> Tc
- **T-matrix** under V(r,T) deduced from lQCD (*TAMU*)





❖ **Radiative Energy Loss**

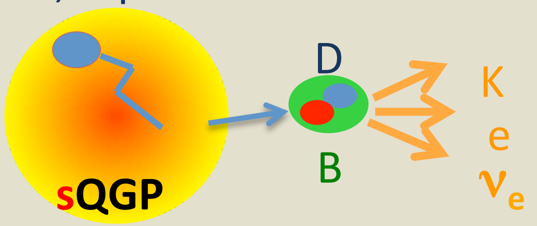
- **pQCD** (p_T > 10 GeV) (*AMY,* ***DGLV****, WHDG,HT,* ***SCET*** …)
  collisional & radiative **both light & heavy, but v_2 often missed**



Agreement that:
- $p \approx m_Q$ is dominated by Collisional E_{loss}
- $p \ggg m_Q$ radiative dominated
- what is the crossing is model dependent and exp. data are not able to clarify it even if favors dominance of collisional up to $p_T \approx$ 6-8 GeV for charm

Standard Dynamics of Heavy Quarks in the QGP

c,b quarks



Brownian Motion

Fokker-Planck approach ($T \ll m_Q$)
in Hydro/transport bulk

$$\frac{\partial f_{c,b}}{\partial t} = \gamma \frac{\partial (p f_{c,b})}{\partial p} + D \frac{\partial^2 f_{c,b}}{\partial p^2}$$

$$\langle p \rangle = p_0 e^{-\gamma t}$$

$$\langle \Delta p^2 \rangle = 3 D_p / \gamma (1 - e^{-2\gamma t})$$

$D_p = ET\gamma$ – Fluct. Diss. Th.

$$\gamma = \int d^3k |M(k,p)|^2 p$$

$$D = \frac{1}{2} \int d^3k |M(k,p)|^2 p^2$$

$|\mathcal{M}|^2$ scatt. matrix from some theory:
HTL, pQCD coll.,rad.,T-matrix

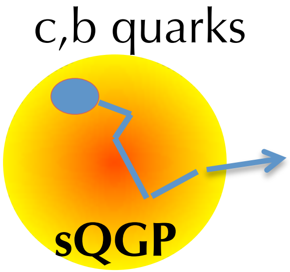
- D_s from latticeQCD

$$D_S = \frac{T}{M\gamma} = \frac{T^2}{D_p} = \frac{T}{M} \tau_{th}$$

A measure of thermalization time

- This is the main set up at east at p< 10 GeV
- Brownian challenged for charm: Boltzmann dynamics
- At p_T> 10 GeV radiative Eloss , qhat, ….

HQ diffusion in the expanding QGP



<u>Two main approaches</u>:

1) **Langevin approach** (T<<m_q soft scattering)

[*TAMU, Duke, Nantes, Torino, Catania, …*]

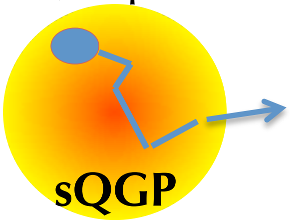
2) **Boltzman kinetic transport** (…Kadanoff-Baym-PHSD)

[*Catania, Nantes, Frankfurt, LBL, CCNU,…*]

background Hydro/transport expanding bulk

HQ diffusion in the expanding QGP

c,b quarks



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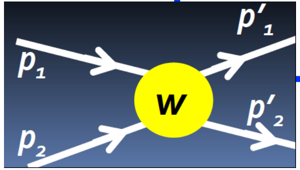
   [*Catania, Nantes, Frankfurt, Berkeley LBL, CCNU,…*]

Boltzmann (BM)

$$\frac{Df_Q(p)}{Dt} = C_{22} = \frac{1}{2E_p}\int\frac{d^3q}{(2\pi)^3 2E_q}\int\frac{d^3p'}{(2\pi)^3 2E'_p}\frac{d^3q'}{(2\pi)^3 2E'_q}\Big[f'_g(q')f'_Q(p')\left|M_{gQ\to gQ}(p'q'\to pq)\right|^2 - f_g(q)f_Q(p)\left|M_{gQ\to gQ}(pq\to p'q')\right|^2\Big](2\pi)^4\delta^4(p+q-p'-q')$$



Small q² <<M, M<< gT
Brownian motion

Langevin/Fokker Planck (LV)

$$\frac{\partial f_Q}{\partial t} = \gamma\frac{\partial(pf_Q)}{\partial p} + D\frac{\partial^2 f_Q}{\partial p^2}$$

<p>≈ e-γT — Drag

<Δp²> — Diffusion

Fluct.-Dissip. Th.
D =ETγ

$$\gamma = \int d^3k\left|M(k,p)\right|^2 p$$

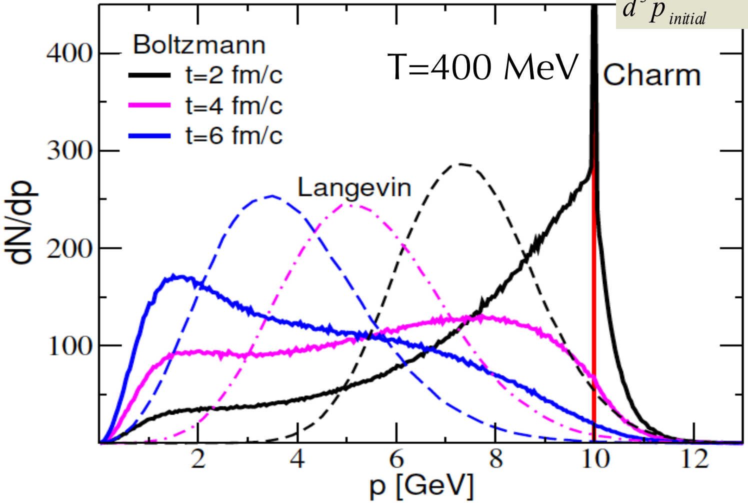
$$D = \frac{1}{2}\int d^3k\left|M(k,p)\right|^2 p^2$$

$|M|^2$ scatt. matrix from some theory:
HTL, pQCD coll.,rad.,T-matrix..

Boltzmann vs Langevin: charm in thermal bath

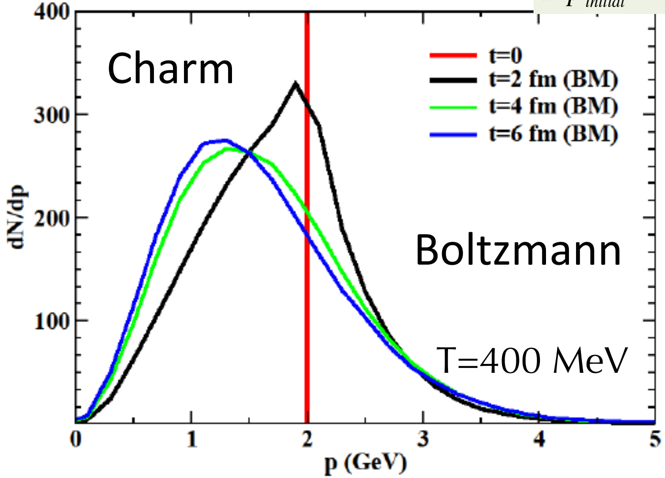
X. Dong & VG, Prog.Part.Nucl.Phys. 104 (2019)

$$\frac{dN}{d^3p}_{initial} = \delta(p - 10GeV)$$



Das et al., PRC90(2014)

$$\frac{dN}{d^3p}_{initial} = \delta(p - 2GeV)$$



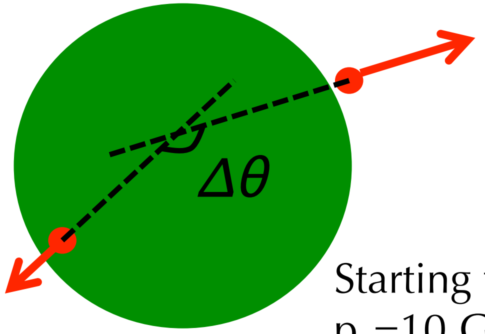
- ✧ Kinematics of collisions (Boltzmann) can throw charm at very low p soon.
- ✧ The motion of single HQ does not appear of Brownian type:
  $M_c/T \approx 3$ -> $M_c/\langle p_{bulk}\rangle \approx 1$ & $p >> m_Q$
- ✧ Evolution of <p> is nearly identical in BM & LV

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{\left(q^2(\theta) + m_D^2\right)^2}$$

$m_D = gT = 0.83$ GeV

Boltzmann for angular correlations

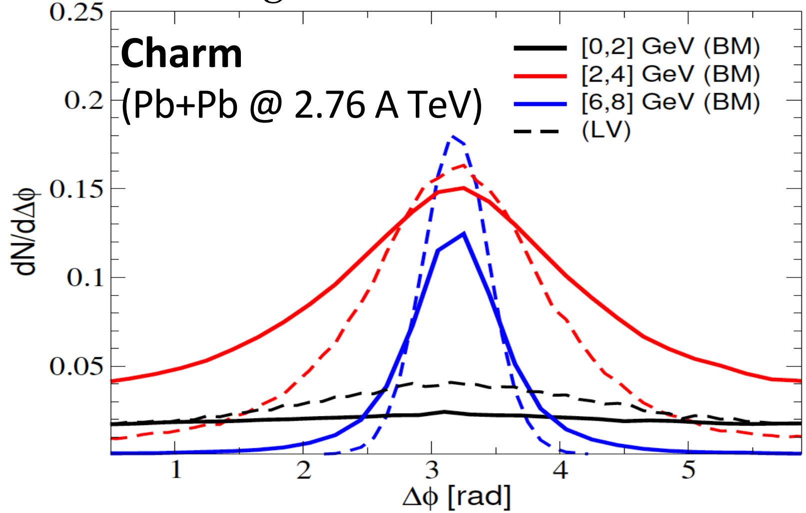
BM vs LV would make a difference for up coming [D-h] + [D-D] triggered angular correlations



p_T [0-2]GeV
p_T [2-4]GeV
p_T [6-8]GeV

Starting from back-to-back p_T=10 GeV as trigger only collisional E_{loss}

Angular correlation



In $dN/d\Delta\phi_{12}$ sizeable differences between BM& LV also for **Bottom**

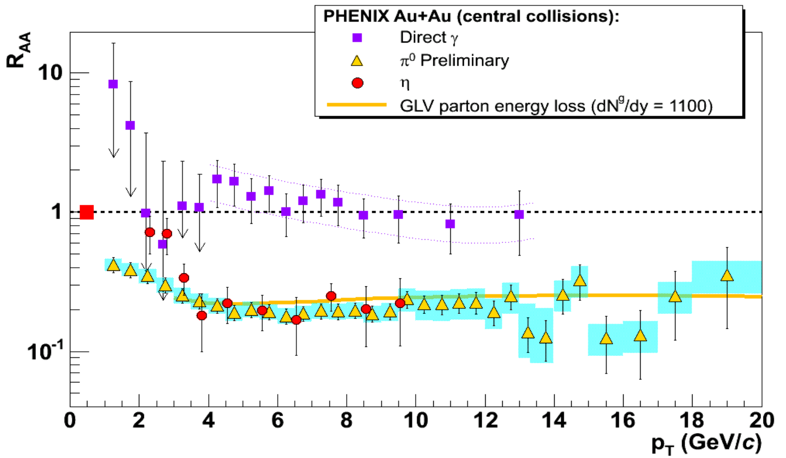
- Boltzmann especially going to $dN/d\Delta\phi_{12}$ and high p_T including both **radiative and collisional** should be more appropriate
  → SUBATECH, LBL- CCNU,…

Two Main Observables in HIC

❖ Nuclear Modification factor

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{N_{coll} d^2N^{NN}/dp_T d\eta}$$

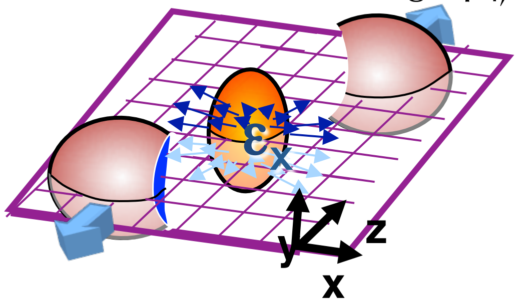
- Modification respect to pp
- Decrease with increasing partonic interaction

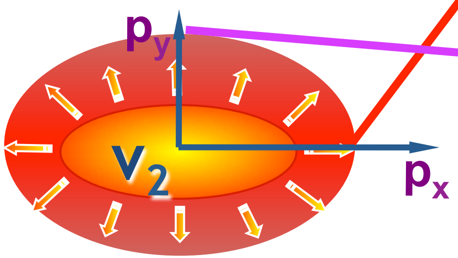


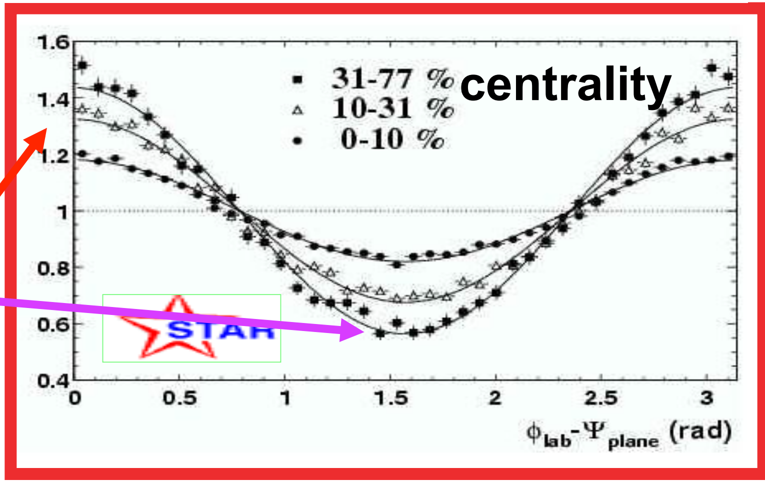
❖ Anisotropy p-space:Elliptic Flow v_2

$$\frac{dN}{p_T dp_T d\varphi} = \frac{dN}{2\pi p_T dp_T}\left[1 + 2v_2\cos(2\varphi) + \ldots\right]$$

both at low & high p_T, but different mechanism

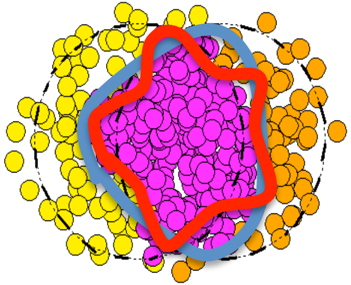






HF dynamics: e-b-e correlations

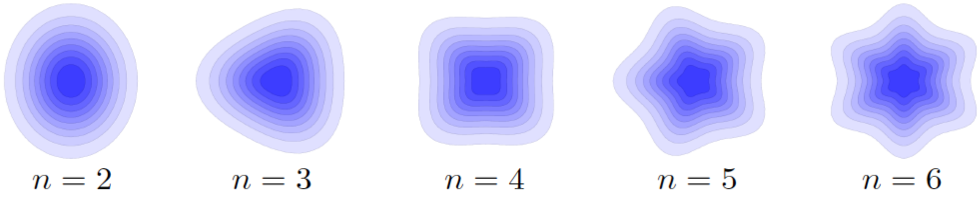
Extending transport approach to event-by-event (space fluctuations in parton distributions):

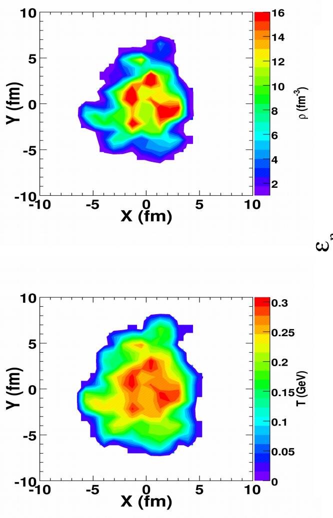


$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\varphi - \Phi_n)] \rangle}{\langle r_\perp^n \rangle}$$

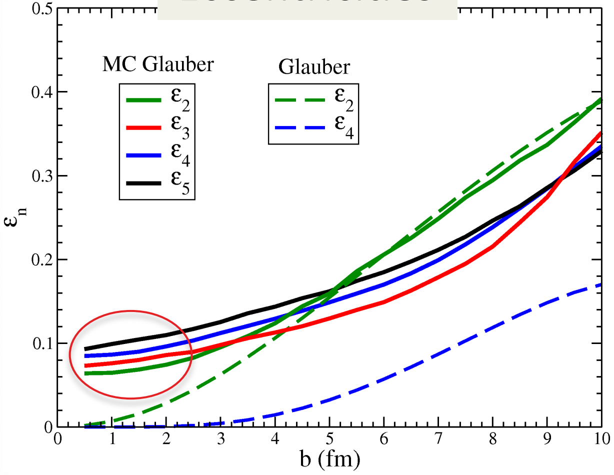
$$\Phi_n = \frac{1}{n} \arctan \frac{\langle r_\perp^n \sin(n\varphi) \rangle}{\langle r_\perp^n \cos(n\varphi) \rangle}$$

When including fluctuations, all moments appear:





Eccentricities



❖ Higher-order (n>2) anisotropies at EIC ?

-> Spatial fluctuations of parton densities

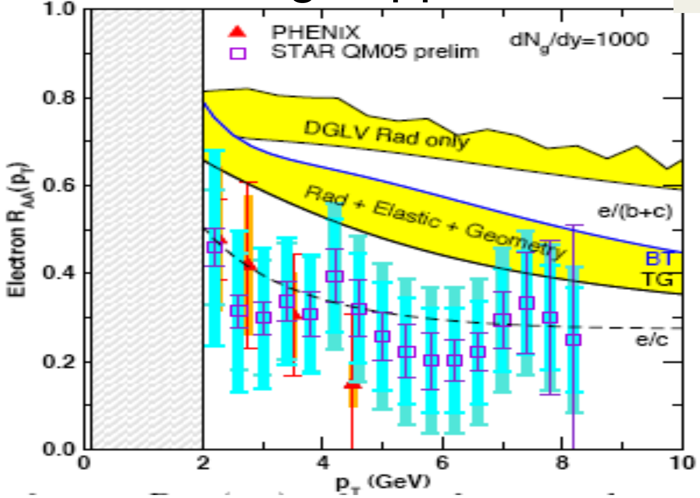
(Sect 3.3. in arXiV:1212.1701 - EIC White Report)

Key importance for QGP study (IP-Glasma)

Surprise at RHIC (≈ 15 years ago)

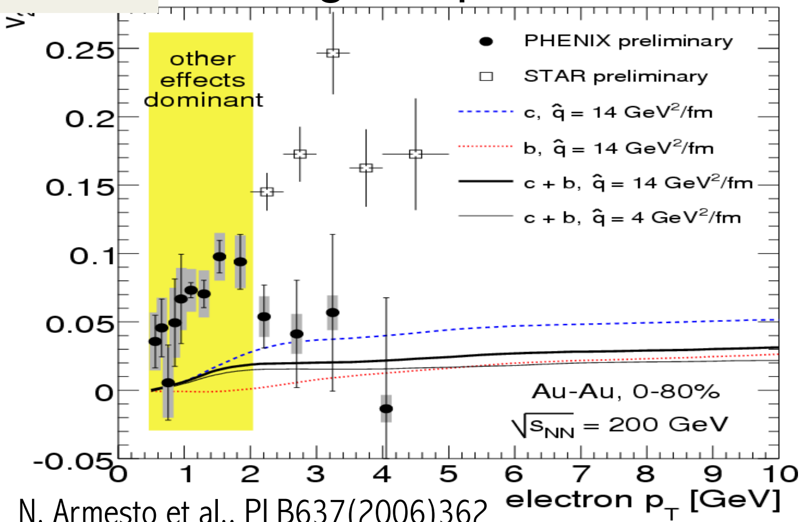
Single e from
D,B semileptonic decay

Strong suppression



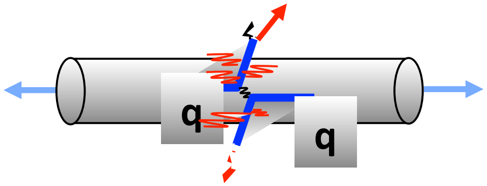
S. Wicks et al. (QM06)

Large elliptic Flow



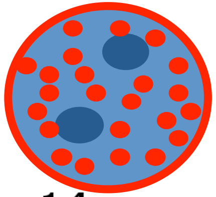
N. Armesto et al., PLB637(2006)362

- ➢ Radiative energy loss not sufficient (p_T<10 GeV)
- ➢ Charm seems to flow like light quarks



pQCD does not work may be the real cross section is a K factor larger?

R_{AA} & v_2 with upscaled pQCD cross section



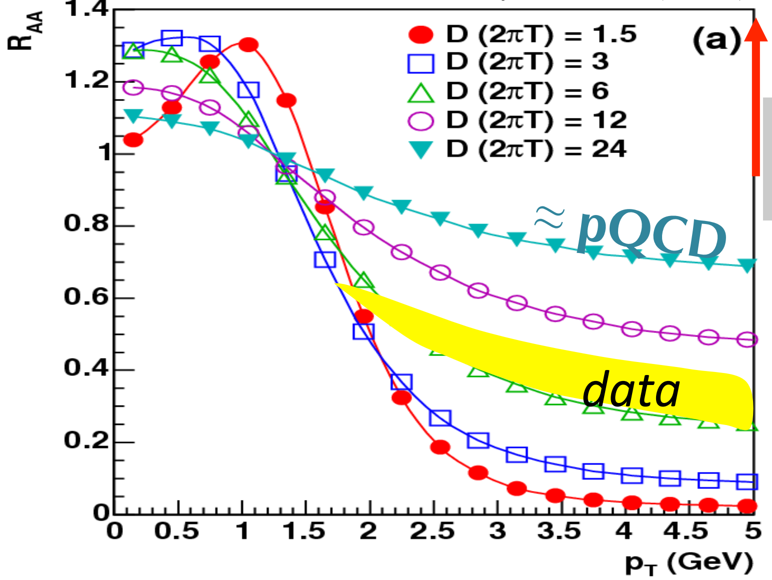
Fokker-Plank for charm interaction in a hydro bulk

Moore & Teaney, PRC71 (**2004**)

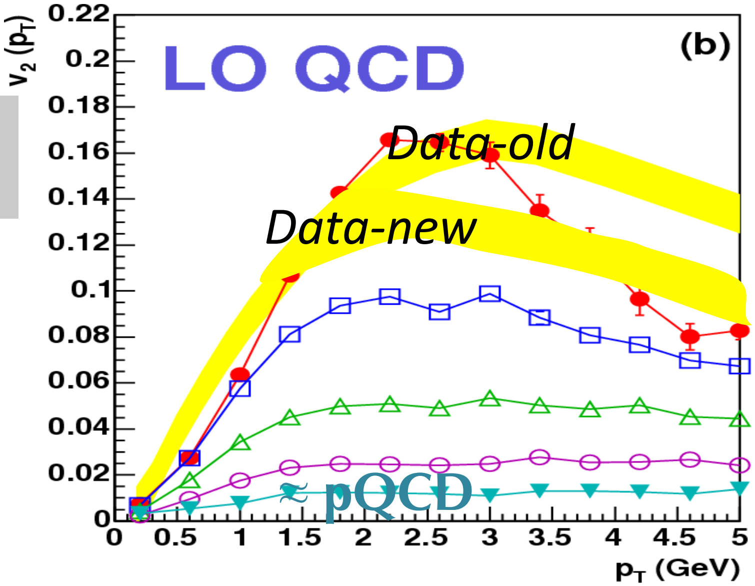
Diffusion coefficient

$$D_p \propto \int d^3k \left| M_{g(q)c \to g(q)c}(k,p) \right|^2 k^2$$

scattering matrix



Multiplying by a K-factor pQCD

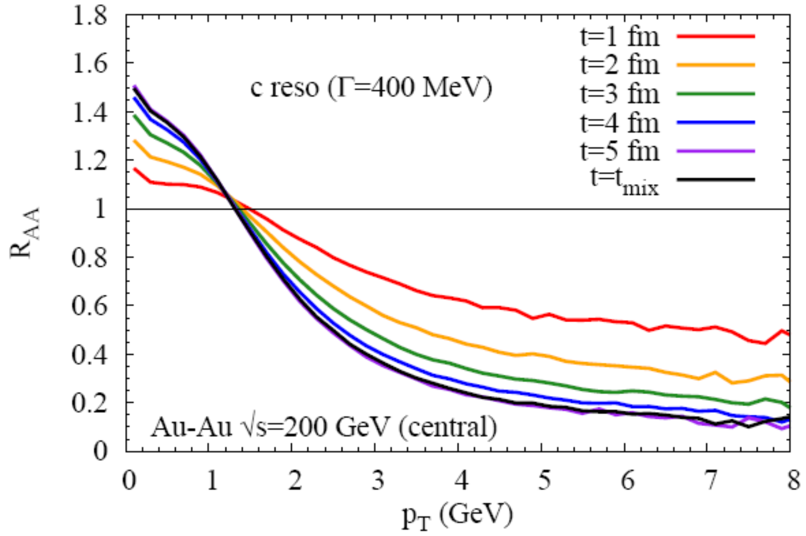


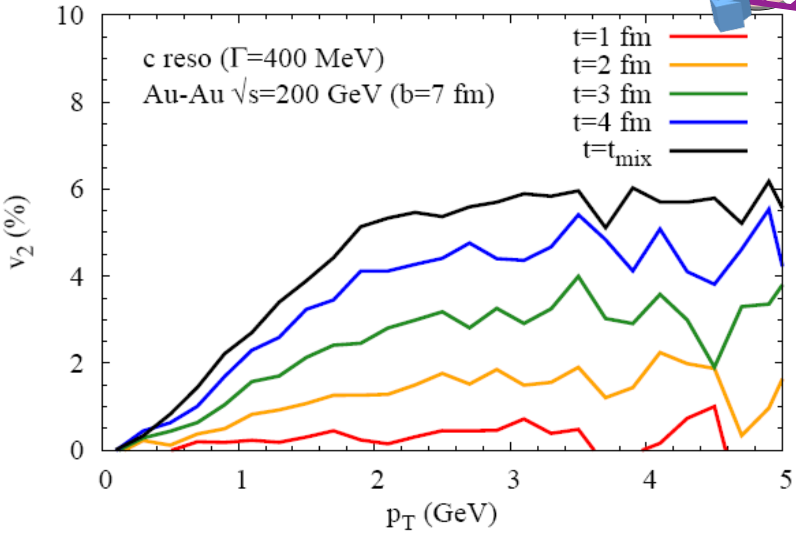
It's not just a matter of pumping up pQCD elastic cross section:
too low R_{AA} or too low v_2

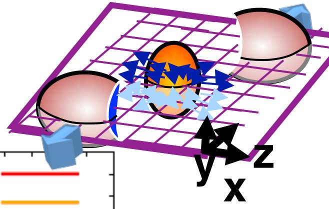
R_{AA} and v_2 correlation: time evolution

R_{AA} can be “generated” faster than v_2

A typical example

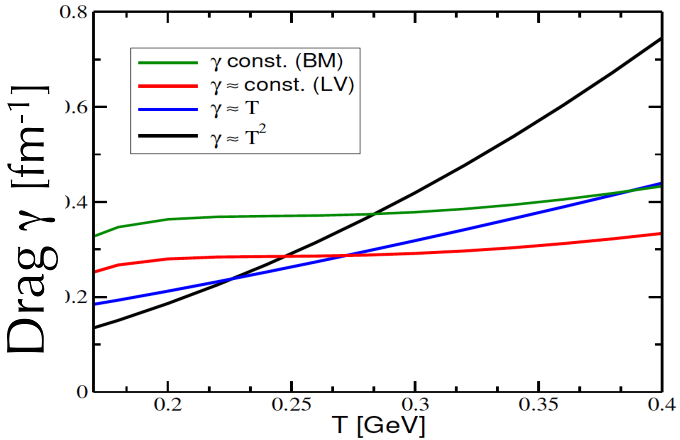






The relation between R_{AA} and time is not trivial and depend on how one interacts and loose energy with time.

Impact of T dep. interaction on $R_{AA} - v_2$

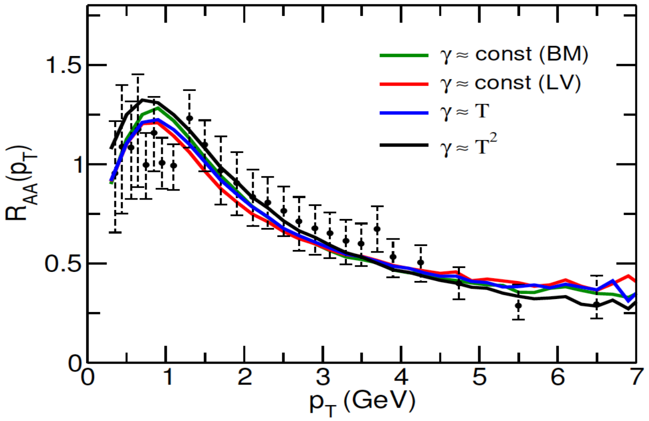


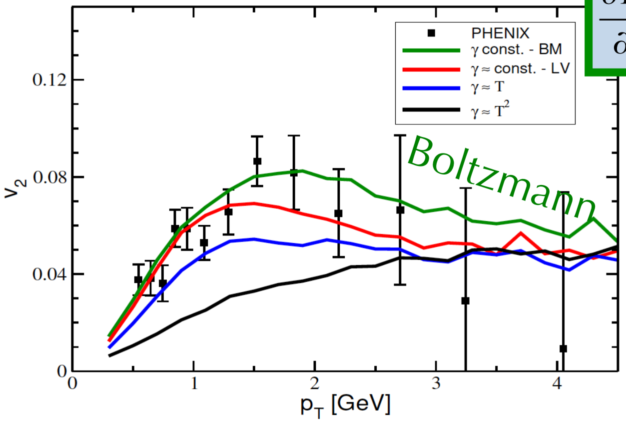
Looking at it beyond the specific modelings

- $\gamma \approx T^2$ [Ads/CFT, pQCD α_s=const, *Duke*]
- $\gamma \approx T$ [pQCD strong α_s running] [MC@HQ] [LBT]
- $\gamma \approx$ **const.** [QPM, PHSD,..] [T-matrix]

γ rescaled to fit $R_{AA}(p_T)$, D from FDT

$$\frac{\partial f_Q}{\partial t} = \gamma \frac{\partial (p f_Q)}{\partial p} + D \frac{\partial^2 f_Q}{\partial p^2}$$





S. Das et al., PLB747 (2015) 260

Simple QP-Model fitting lQCD

Plumari, Alberico, Greco, Ratti, PRD84 (2011)

$$P(T) = \sum_{i=g,q,\bar{q}} \frac{D_i}{(2\pi)^3} \int_0^\infty d^3k \frac{k^2}{3\omega_i(k)} f_i(k) - B(T)$$

$$\varepsilon(T) = \sum_{i=g,q,\bar{q}} \frac{d_i}{(2\pi)^3} \int_0^\infty d^3k \; \omega_i(k) \; f_i(k) + B(T) + \widetilde{W}_B(T)$$

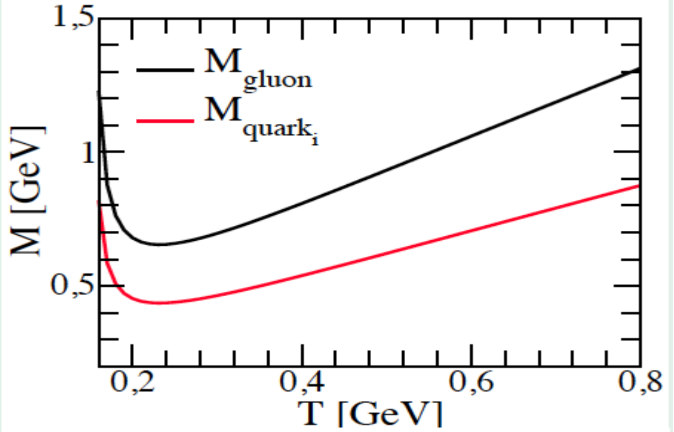
Interaction in thermal quasi-particle masses + B(T)

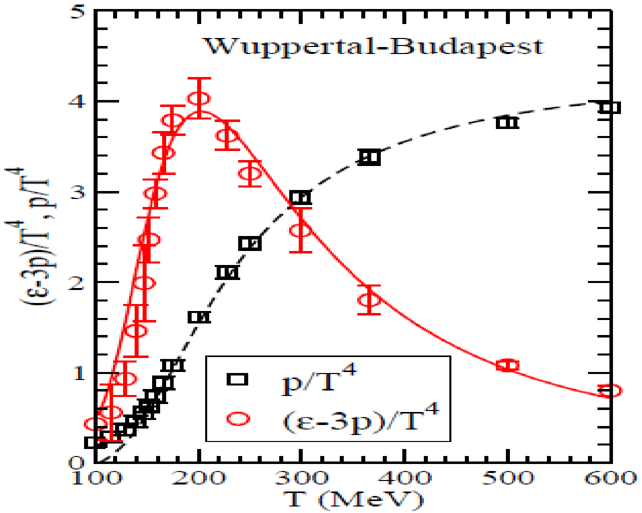
$$\omega_{q,g} = k^2 + m^2_{q,g}(T) \qquad m_g^2 = \frac{1}{6}\left(N_c + \frac{1}{2}N_f\right) g^2T^2 \qquad m_q^2 = \frac{N_c^2 - 1}{8N_c} g^2T^2($$

g(T) from a fit to **ε** from lQCD
-> good reproduction of P, e-3P, c_s

$$g^2_{QP}(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2}$$

λ=2.6
T_s=0.57 T_c

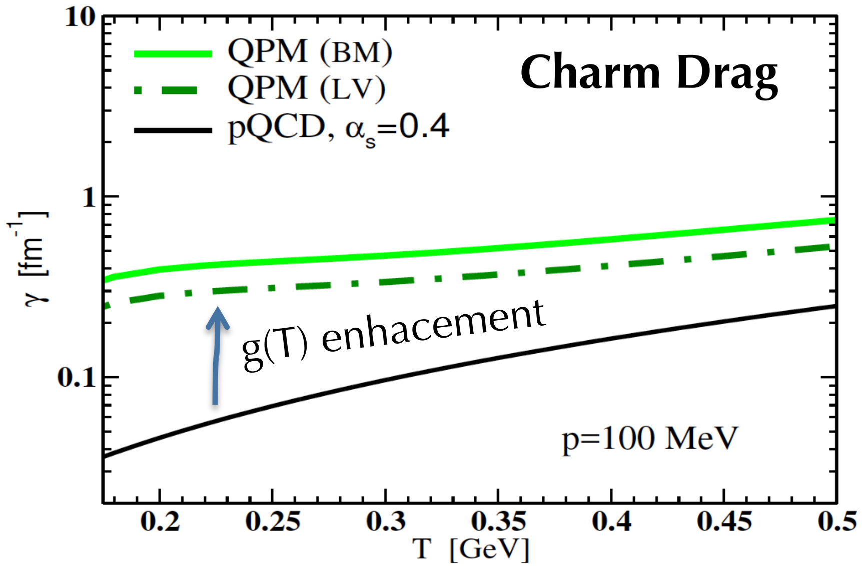




<u>**Main features**</u>: as T→Tc enhancement of the coupling
reminescent of confinement dynamics,

Similarly for T-Matrix with V(r,T) deduced from lattice QCD

Drag Transport coefficient in QPM

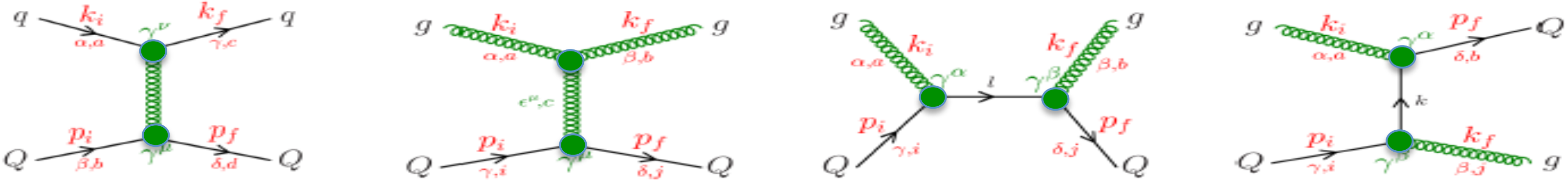


$f(p,t=0)=\delta(p-p_0)$

$<p>=p_o\ e^{-\gamma t}$

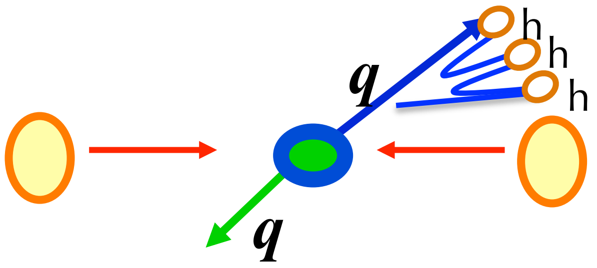
- ✧ Drag from QPM quite large than pQCD : g(T) enhanced as T-->Tc weak dependence on T
- ✧ pQCD or AdS/CFT $\gamma\ (T)\approx 1/T^2$

$$\gamma_i=\gamma(p^2)p_i=\frac{1}{2E_p}\int\frac{d^3q}{(2\pi)^3 2E_q}\int\frac{d^3q'}{(2\pi)^3 2E_{q'}}\int\frac{d^3p'}{(2\pi)^3 2E_{p'}}\sum\left|M_{(q,g)+Q\to(q,g)+Q}\right|^2(2\pi)^4\delta^4(p+q-p'-q')f(q)\left[(p-p')_i\right]$$



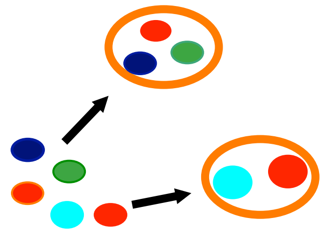
Fragmentation: e^+e^-, ep, pp

$$f_H(P_H = zp_T) = f_{q,g}(p_T) \otimes D_{q,g\to H}(z) \quad , z<1$$

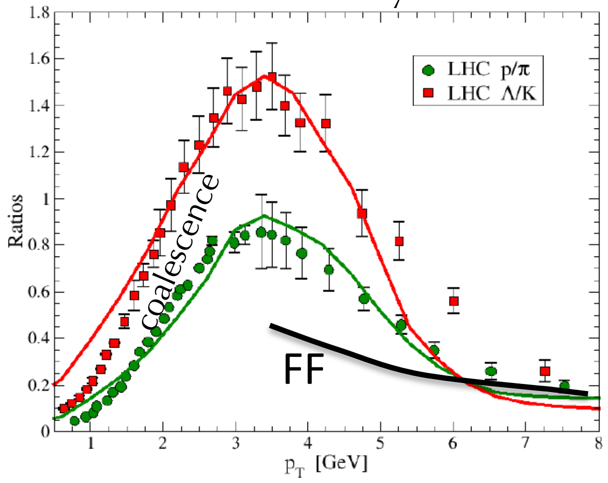


Quark recombination

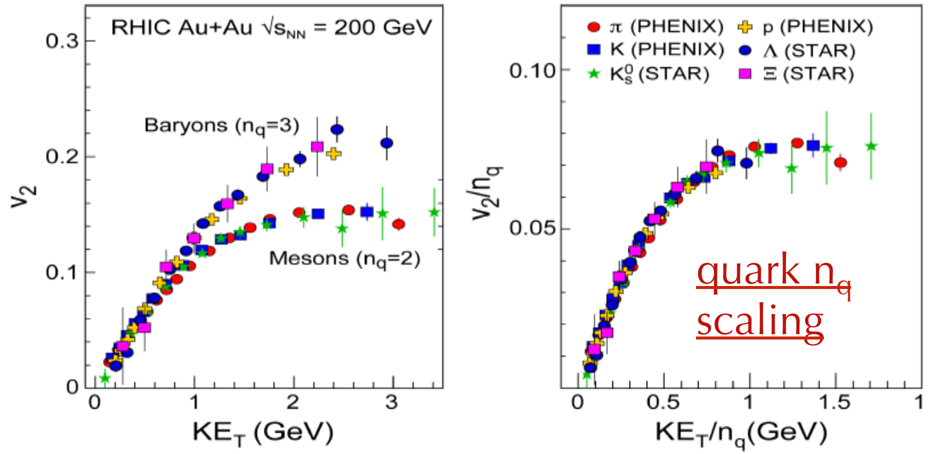
$$f_M(P = p_a + p_b) = \sum_{a,b} f_a(r_a,p_a) \otimes f_b(r_b,p_b) \otimes \Phi_M\left(r_{ab},q_{ab}\right)$$



Ratio B/M in Hadr. by Coalecence

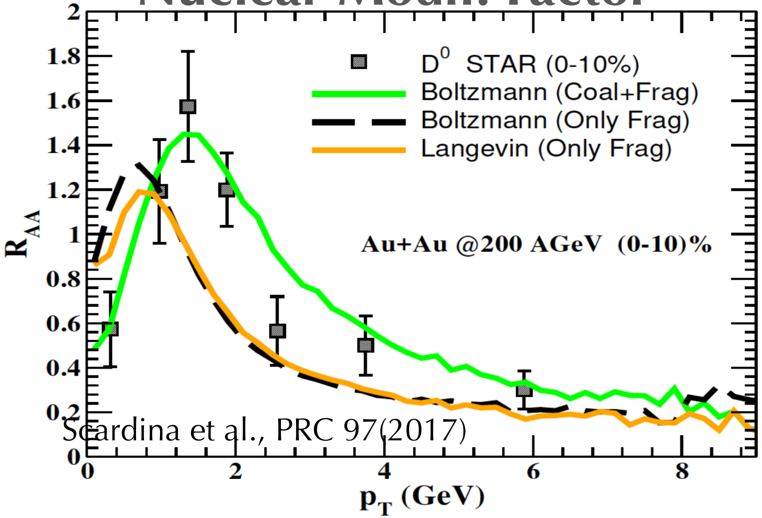


B/M Elliptic flow

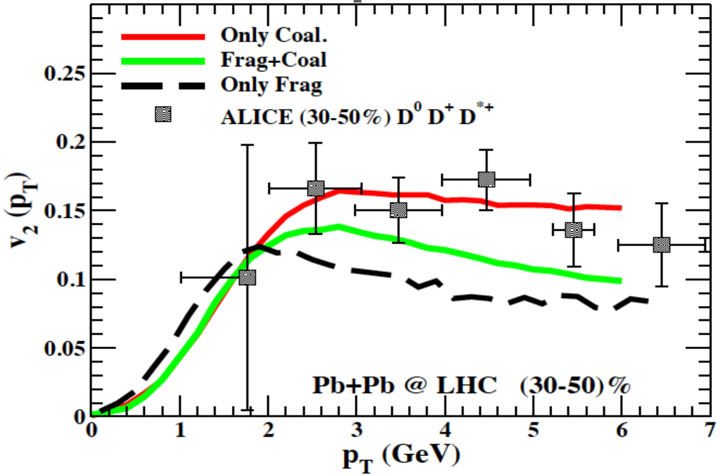


Some predictions…

Nuclear Modif. Factor



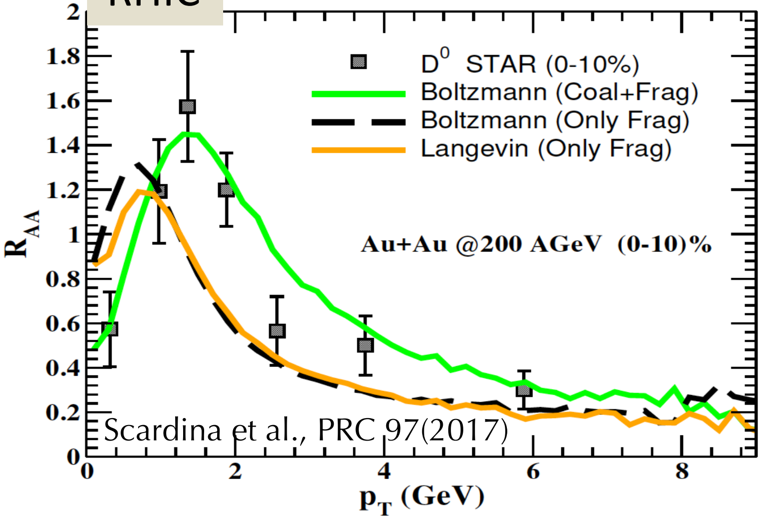
Elliptic flow



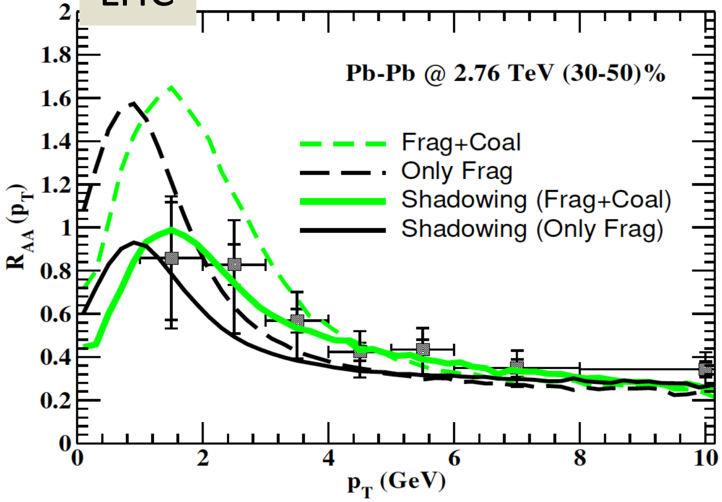
- ✓ Coalescence for D *brings up both* R_{AA} *and* v_2 *toward data*

Some predictions…

RHIC



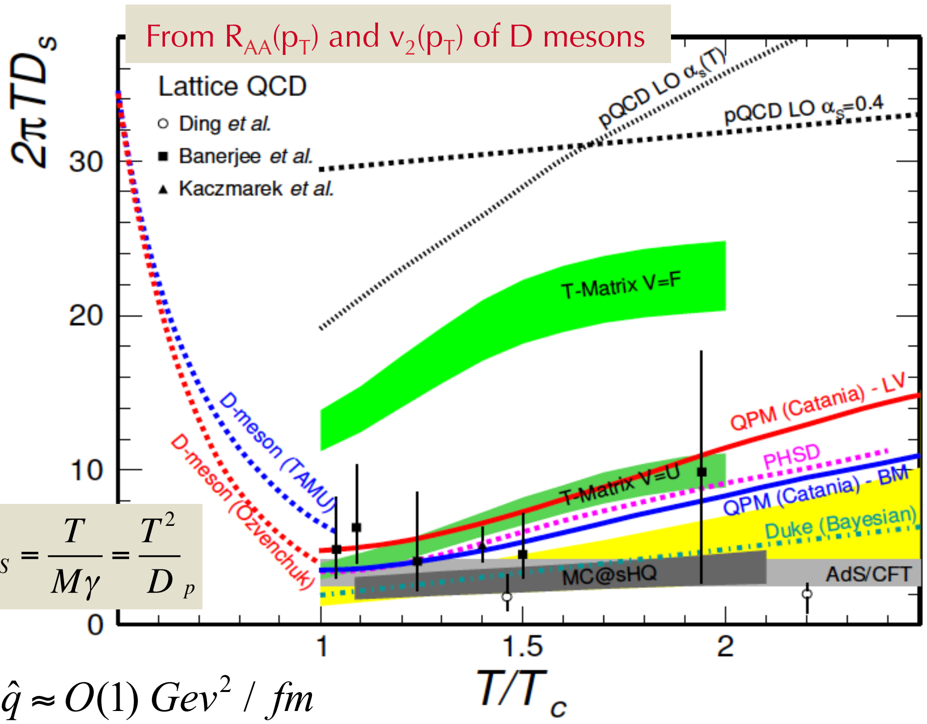
LHC



- ✓ Coalescence for D *brings up both R_{AA} and v_2 toward data*
- ✓ @LHC shadowing appear necessary [EPS09, Eskola-Salgado JHEP(2009)]
- ✓ EIC on shadowing + new data → much more quantitative statements
- ✓ Hadronic rescattering does not change R_{AA}, increase by 15% v_2

What is the underlying D_s?

X. Dong & VG, Progr. Part. Nucl. Phys.(2019)



$$D_s = \frac{T}{M\gamma} = \frac{T^2}{D_p}$$

$$\hat{q} \approx O(1)\ Gev^2 / fm$$

$$\tau_{th} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8\,\frac{2\pi T D_s}{(T/T_c)^2}\ \text{fm/c}$$

$$\tau_{therm} \approx \tau_{QGP} \approx 5\ \text{fm/c}$$

- Largely non-perturbative Ds (close AdS/CFT)
- Agreement with lattice QCD

*Main Differences in models:
- impact of **hadronization**
- **momentum depedence of diffusion**
- **inclusion of radiation**
- not all models describe data with the same quality

Future:
- Access low p & precision data (detector upgrade)
- Better insight into hadronization (…EIC)
- New observables
- Bottom

Reviews:
- F. Prino and R. Rapp, JPG(2019)
- X. Dong and VG, Prog.Part.Nucl.Phys. (2019)
- Jiaxing Zhao et al., arXiv:2005.08277

Linearized Boltzmann: Coll.+Rad.

Linearized Boltzmann Transport : Rad.(pQCD) + Coll. E_{loss} (K*pQCD)

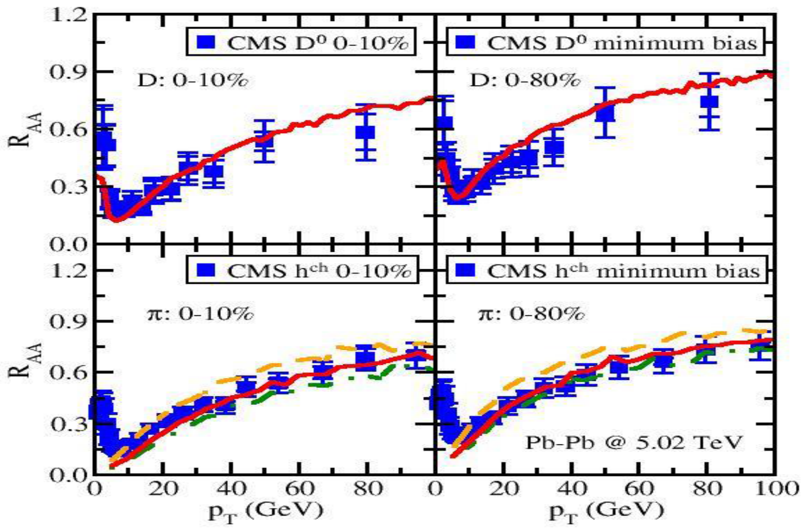
Inelastic Scatt. probability based on the average number of medium-induced gluon

Spectrum of medium-induced gluon (Higher-Twist formalism):

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A P(x)}{\pi k_\perp^4} \hat{q} \left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2} \right)^4 \sin^2 \left(\frac{t - t_i}{2\tau_f} \right)$$

[Guo- Wang (2000), Majumder (2012); Zhang, Wang-Wang (2004)]

Number n of radiated gluons during Δt – Poisson distribution: $P(n) = \frac{\langle N_g \rangle^n}{n!} e^{-\langle N_g \rangle}$ $\quad P_{\text{inel}} = 1 - e^{-\langle N_g \rangle}$



S.Cao, Luo, Qin and Wang, Phys.Rev.C 94 (2016)

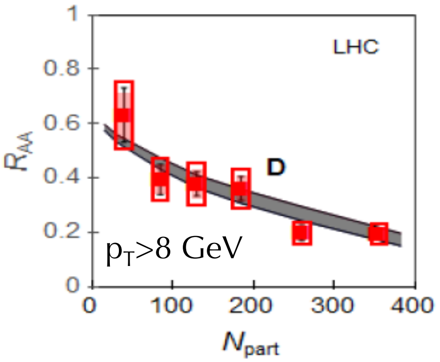
- ✧ Both heavy and light
- ✧ Both radiative and collisional
- ✧ Realistic hydro background

Radiation: pQCD E_{loss} extension of DGLV

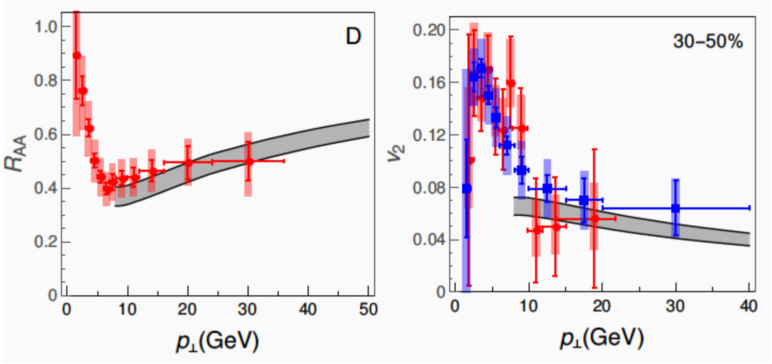
Continous improvement on GLV: no static scatterings → collisional+radiative, finite size, magnetic and electric mass, α_s running …:

$$\frac{E_f d^3\sigma}{dp_f^3} = \frac{E_i d^3\sigma(Q)}{dp_i^3} \otimes P(E_i \to E_f) \otimes D(Q \to H_Q) \otimes f(H_Q \to e, J/\psi)$$

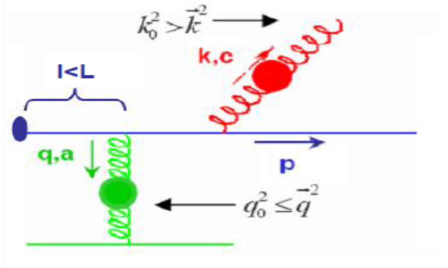
- Collisional non negliglible (also at p_T>5-10 GeV)
- Explain $R_{AA}(\pi) \approx R_{AA}(D) < R_{AA}(B)$



M. Djordjevic et al., PLB734 (2014)



D. Zigic et al, PLB791(2019)



HTL Electric & magnetic propagators an approach for Hot matter

Radiative parton Eloss accounts for R_{AA} , v_2 of both light and heavy quarks at p_T> 8-10 GeV

✧ In the past was missing an underlying Hydro background: Under progress (3+1D) calculation → $v_2(p_T)$

Open HQ in soft-collinear effective theory (SCET)

✧ **Effective theory [power counting in p_T/Q]** describing the propagation of HQ in a background QCD medium – $\text{SCET}_{M,G}$ **beyond parton Eloss**

✧ Role of **mass** understood in vacuum & medium
splitting functions that in the limit of soft emission reduce to GLV

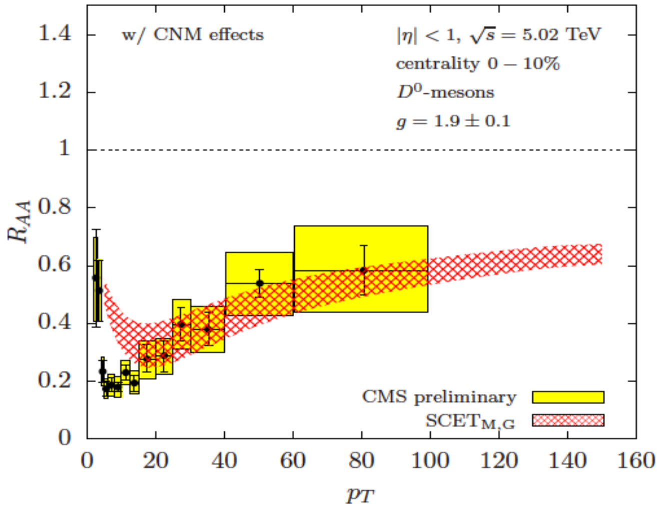
Massive splitting function with dead cone
Consistent full NLO calculation

$$\sum_j \hat{\sigma}_i^{(0)} \otimes \mathcal{P}_{i\to jk}^{\text{med}} \otimes D_j^H \equiv \hat{\sigma}_i^{(0)} \otimes D_i^{H,\text{med}}$$

✧ Confirm Radiative process (p_T> 20 GeV)
✧ Approach applies in both cold and hot matter (≠DGLV)
→ **predictions for EIC**

Not applied to study v_n (to my knowledge)

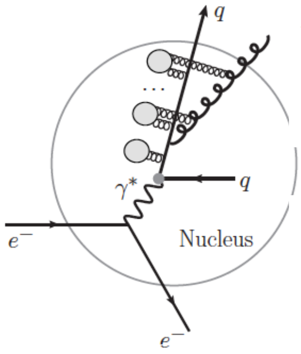
Z. Kang, F. Ringer, I. Vitev, JHEP 03 (2017)



p_T

At lower p_T including collisional **Dissociation** of D meson ($\tau_D = \tau_0 * E/m_D$)

SCET+DGLAP-FF for EIC



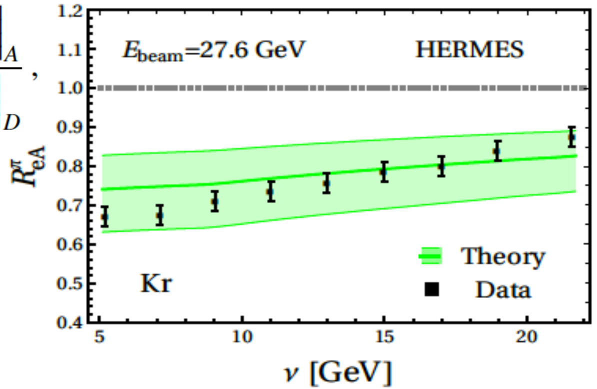
$$E_h \frac{d^3\sigma^{\ell N \to hX}}{d^3 P_h} = \frac{1}{S} \sum_{i,f} \int_0^1 \frac{dx}{x} \int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu) \times D^{h/f}(z,\mu) \left[\hat{\sigma}^{i \to f} + f_{\rm ren}^{\gamma/\ell}\left(\frac{-t}{s+u}, \mu\right) \hat{\sigma}^{\gamma i \to f} \right].$$

$$\frac{d}{d \ln \mu^2} \tilde{D}^{h/i}(x,\mu) = \sum_j \int_x^1 \frac{dz}{z} \tilde{D}^{h/j}\left(\frac{x}{z},\mu\right) \times \left(P_{ji}(z,\alpha_s(\mu)) + P_{ji}^{\rm med}(z,\mu)\right)$$

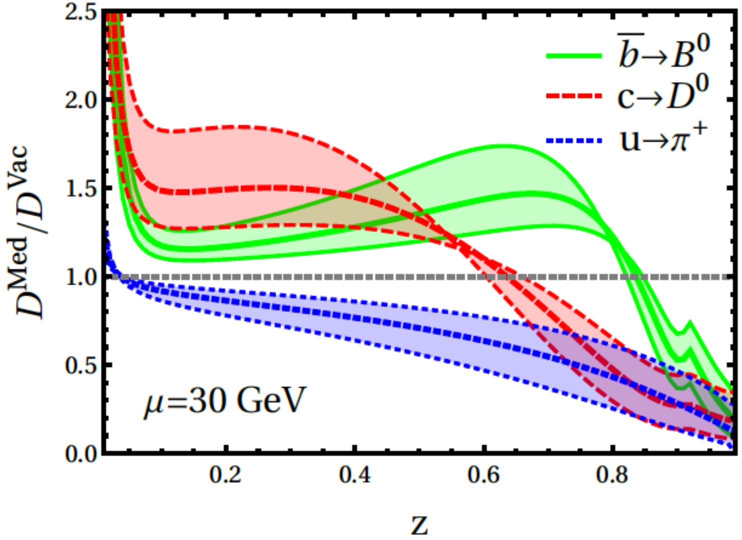
- SCET: jet – QCD medium interaction as in AA
- Medium induced splitting kernels →FF evolution

New evolution approach with in-medium showers, NLO baseline. Constrained by HERMES.

$$R_{eA}^{\pi}(\nu, Q^2, z) = \frac{\left.\frac{N^\pi(\nu,Q^2,z)}{N^e(\nu,Q^2)}\right|_A}{\left.\frac{N^\pi(\nu,Q^2,z)}{N^e(\nu,Q^2)}\right|_D},$$

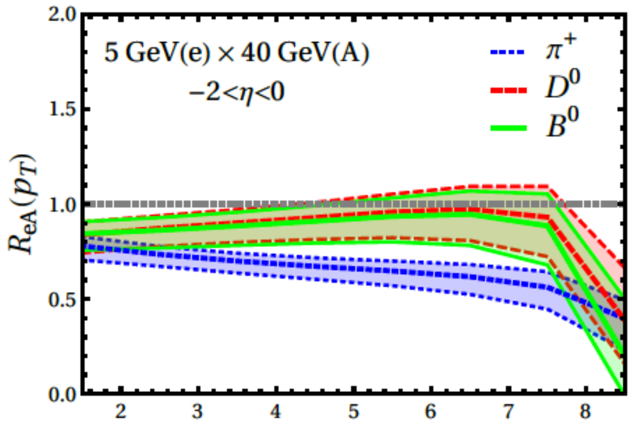


H.T. Li, Z.L. Liu, I. Vitev, 2007.10994



Enhancement at small and moderate values of z. Induced by the hard vacumm fragmentation

SCET+DGLAP-FF: predictions for EIC

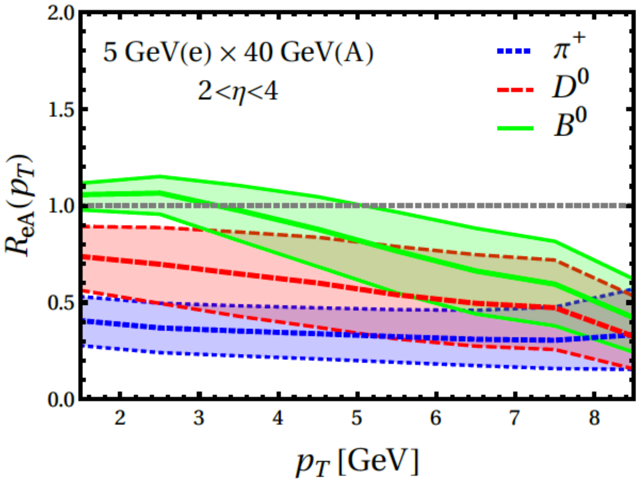


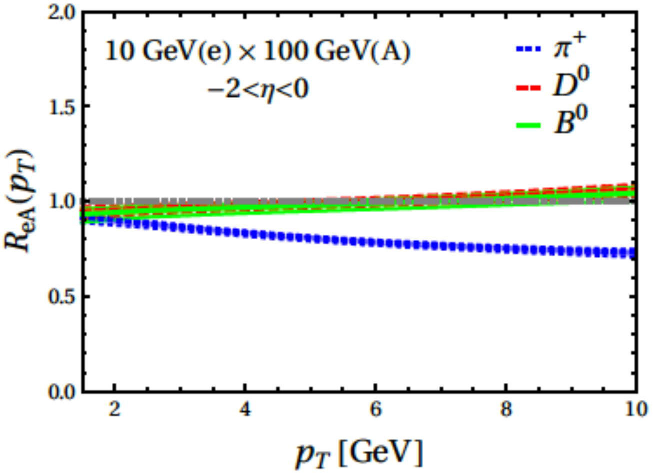
$$R^{\pi}_{eA}(\nu, Q^2, z) = \frac{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_A}{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_D},$$

H.T. Li, Z.L. Liu, I. Vitev, 2007.10994

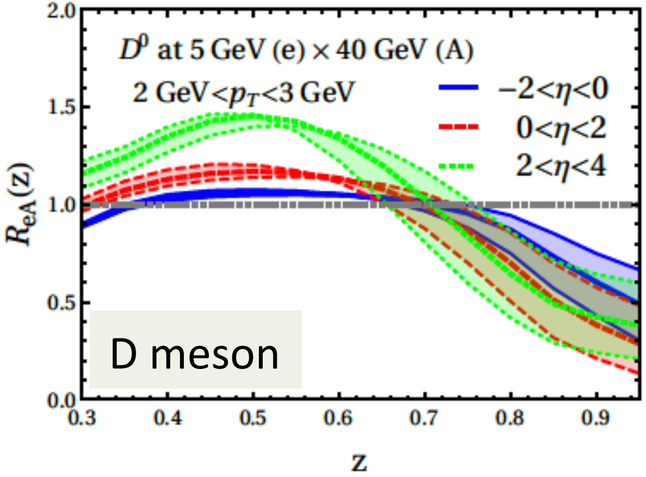
✧ First predictions: how nuclear effects will change with P_T and rapidity

✧ Effects larger at smaller energy and rapidity gap

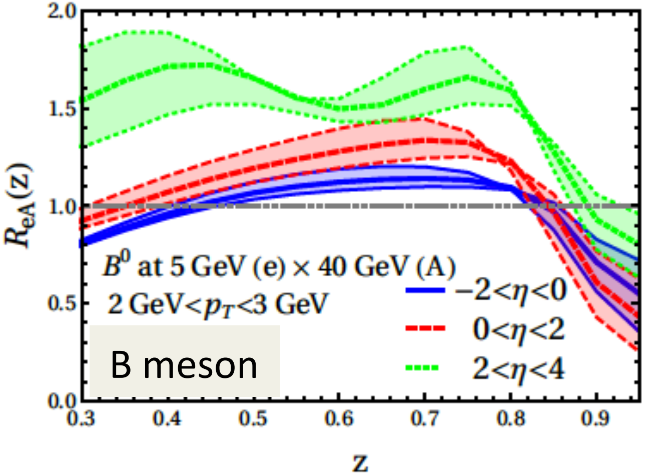




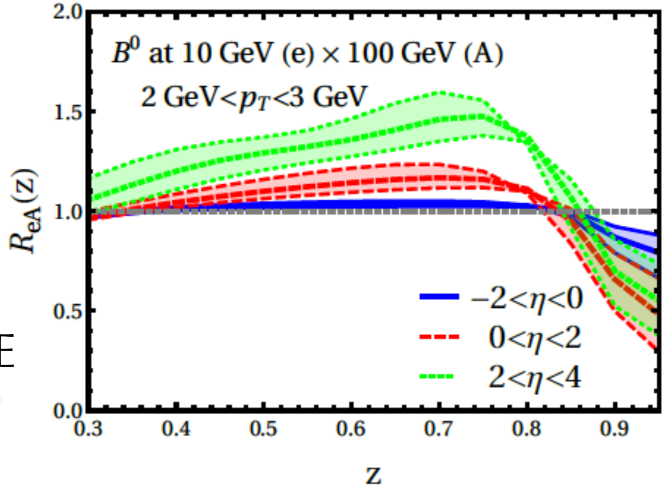
SCET+DGLAP-FF: prediction for EIC



- ✧ For D and B the R_{eA} vs z is closely related to Fragmentation Function in-medium modification: more suitable observable for tomography
- ✧ Transition from enhancement to suppression at moderate z will be an *unambigous measure of parton shower formation* in Nuclei

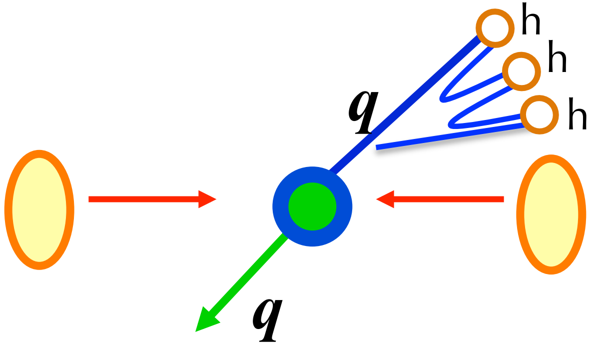


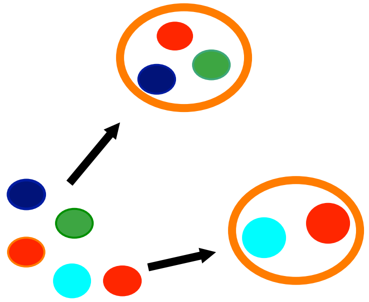
Increasing E →



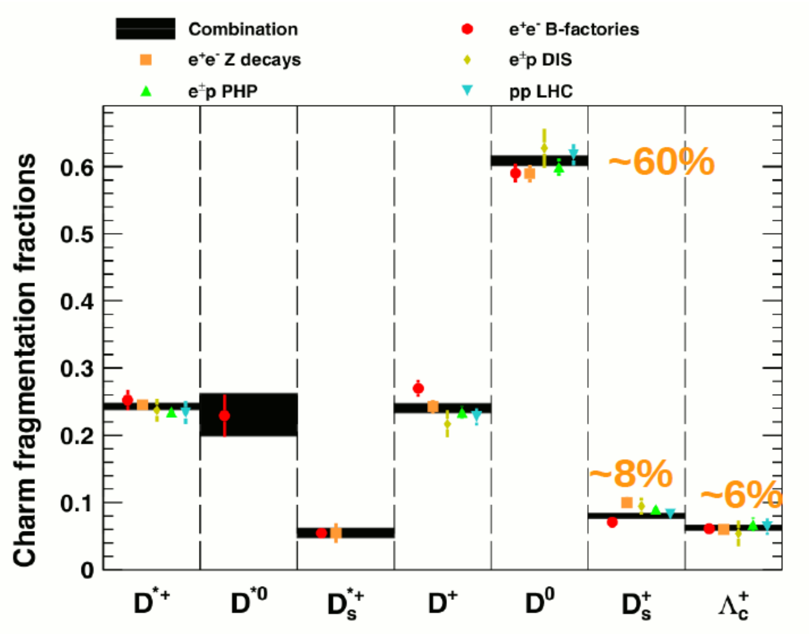
HADRONIZATION

(AA,pA…pp)





Λ_c/D in elementary collisions



M. Lisovyi, et al. EPJ C76 (2016) no.7, 397

Fragmentation functions

$$\left(\frac{\Lambda_C}{D^0}\right)_{\substack{e^+e^-\\pp}} \approx 0.1$$

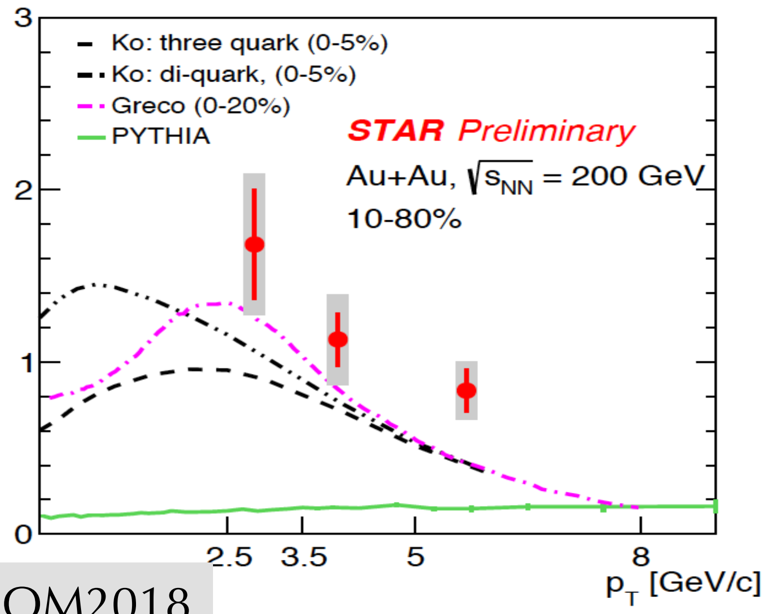
Statistical Hadronization model

$$\left(\frac{\Lambda_C}{D^0}\right)_{\substack{e^+e^-\\pp}} \approx 0.25 - 0.30$$

A. Andronic et al. PLB571 (2003)
I. Kuznetsova, J. Rafelski, EPJ C51 (2007)

Λ_c/D in AA and in pp

Quite surprising …



QM2018

Large Λ_c/D predicted by quark coalescence in the QGP

Y. Oh, C.M. Ko, et al., PRC79 (2009)
S. Plumari, V. Minissale and V.G., Eur. Phys. J. C78(2018)

Coalescence approach

Statistical factor colour-spin-isospin — **Parton Distribution function** — **Hadron Wigner function**

$$\frac{dN_{Hadron}}{d^2 p_T} = g_H \int \prod_{i=1}^{n} p_i \cdot d\sigma_i \frac{d^3 p_i}{(2\pi)^3} f_q(x_i, p_i)\, f_W(x_1, \ldots, x_n; p_1, \ldots, p_n)\, \delta\left(p_T - \sum_i p_{iT}\right)$$

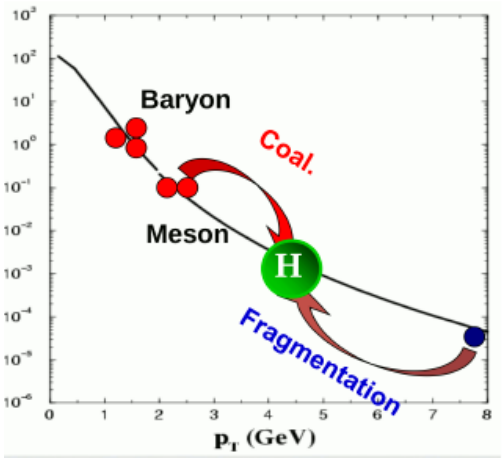
distribution function giving R_{AA} and v_2 for D just discussed

Wigner function with the width fixed by radius from quark model

C.-W. Hwang, EPJ C23, 585 (2002).
C. Albertus et al., NPA 740, 333 (2004 quark model

$\langle r^2 \rangle_{D^+} = 0.184\, fm^2$ $\quad \langle r^2 \rangle_{D_s^+} = 0.124\, fm^2$ $\quad \langle r^2 \rangle_{\Lambda_c^+} = 0.152\, fm^2$

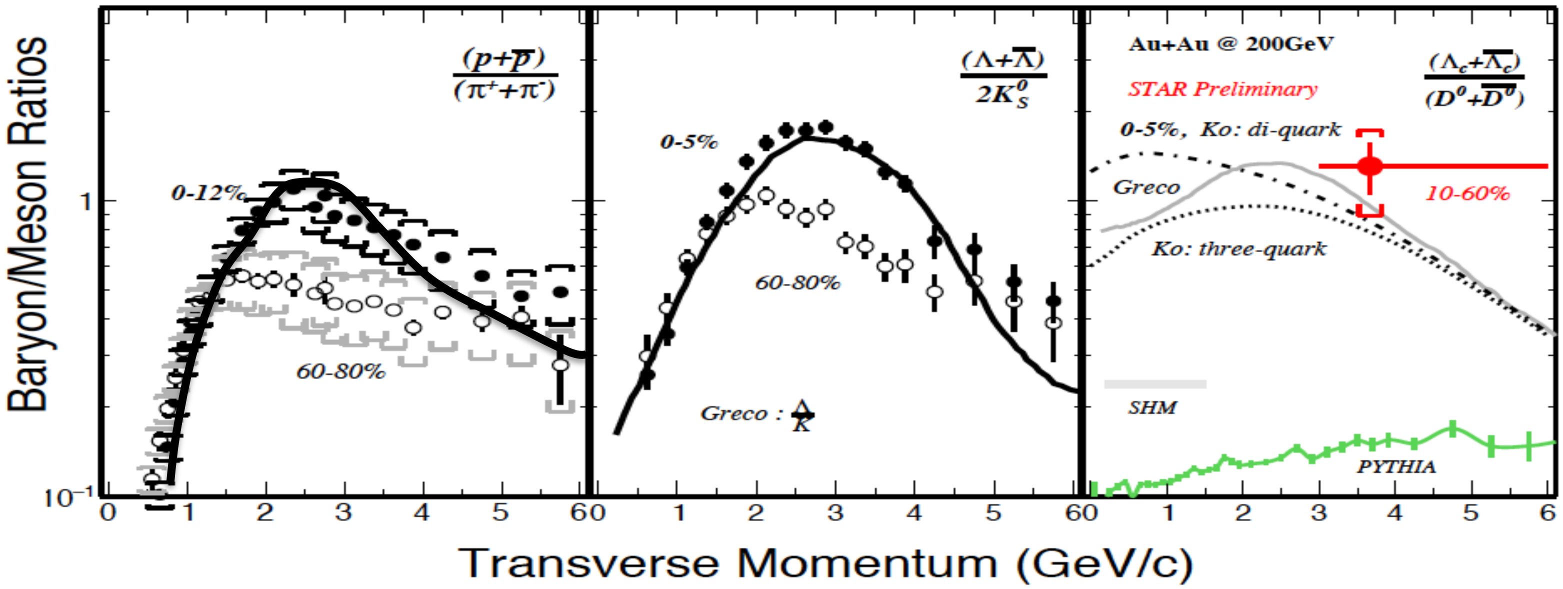
Requiring Pcoal(p→0)=1



Greco-Ko Levai, Phys. Rev. Lett. (2003)

- ✧ The charm not "coalescencing" undergo fragmentation: charm number conserved at each p_T
- ✧ Is the same approach employed to predict p/π, Λ/K

Coalescence in AA for p/π Λ/K, Λc/D?

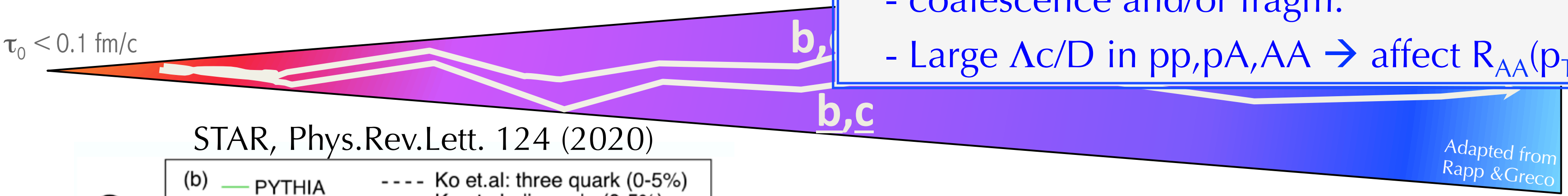


X. Dong and V. G., Progress in Particle and Nuclear Physics (2018)

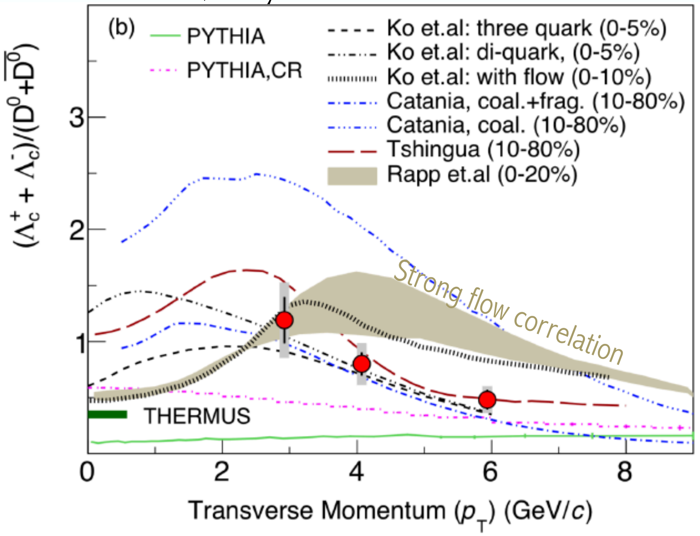
Greco-Ko Levai, Phys. Rev. Lett. (2003)

Studying the HF in uRHIC

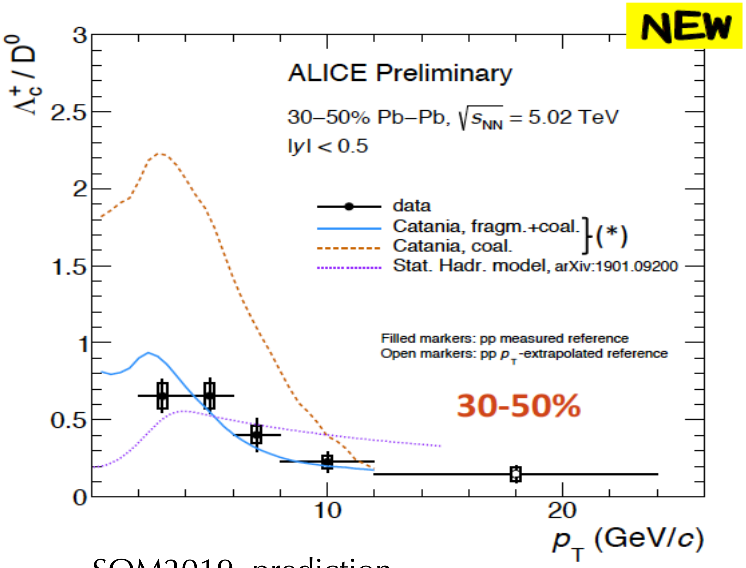
- **Hadronization $\Lambda_C/D \approx O(1)$**
  - coalescence and/or fragm.
  - Large $\Lambda c/D$ in pp,pA,AA → affect $R_{AA}(p_T)$



STAR, Phys.Rev.Lett. 124 (2020)



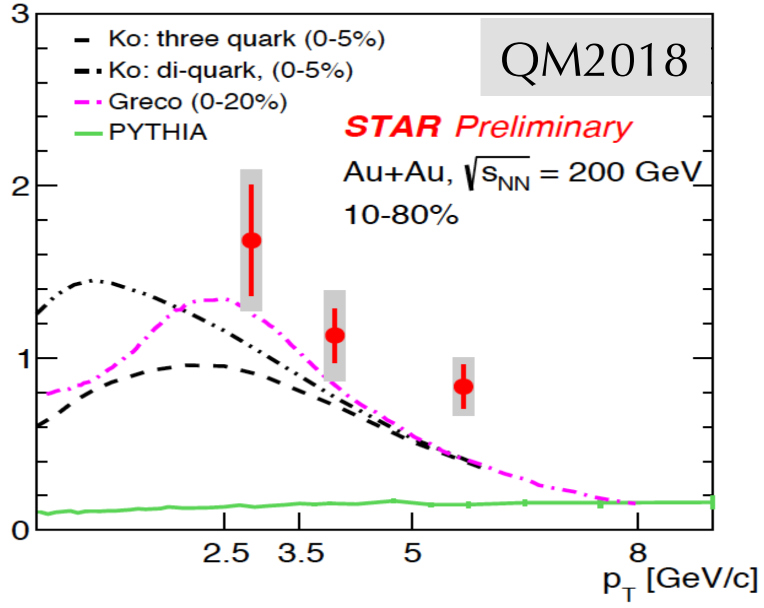
He,Rapp: RQM >> PDG



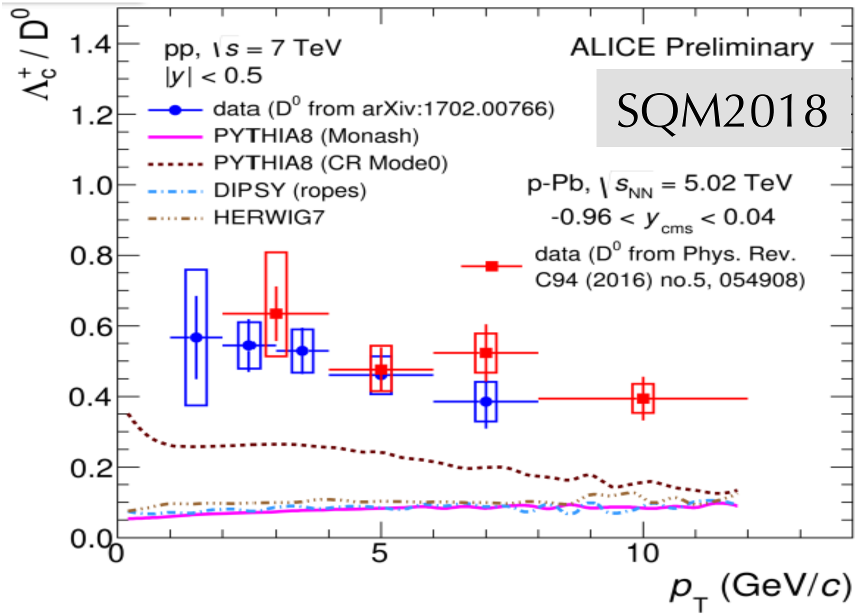
SQM2019, prediction

Λ_c/D in AA and in pA,pp

Quite surprising in AA …



but even in **pp@7TeV & pA@5TeV**



Large Λ_c/D predicted by quark coalescence in the QGP

Is there a Hot QCD matter medium also in pA and pp?
Several signatures of flow expansion in high multiplicity pp and pA also for HQ

PRELIMINARY

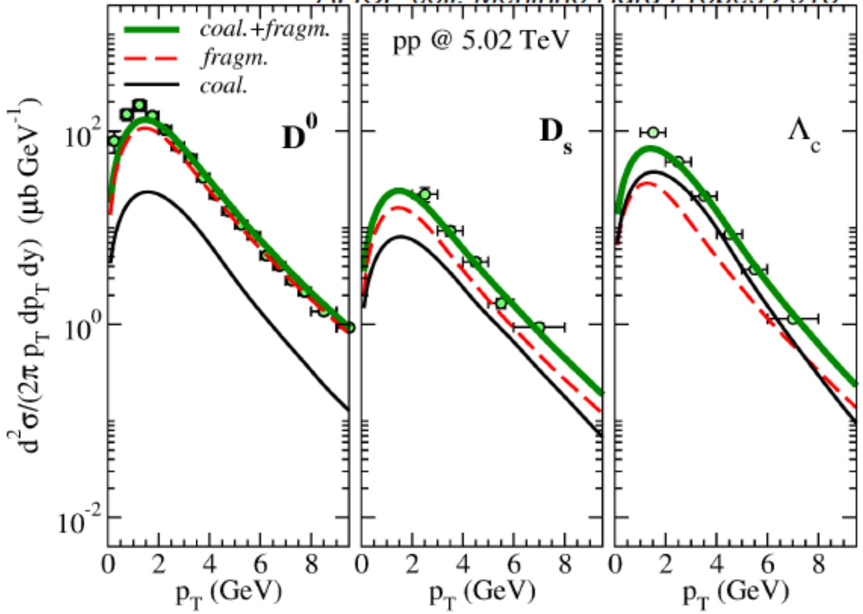
Small systems: Coalescence in pp?

Common consensus of possible presence of QGP in smaller system.

What if:

- **Assuming QGP formation also in pp?**
- **What coalescence+fragmentation predicts in this case?**

Data taken from: ALICE coll. EPJ C79 (2019) no.5, 388
ALICE coll. Meninno Hard Probes 2018



If we assume in p+p @ 5 TeV a mediun similar to the one simulated in hydro:

- Thermal Distribution (p_T< 2 GeV)

$$\frac{dN_q}{d^2 r_T d^2 p_T} = \frac{g_q \tau m_T}{(2\pi)^3} \exp\left(-\frac{\gamma_T(m_T - p_T \cdot \beta_T)}{T}\right)$$

- Collective flow $\beta_T = \beta_0 \frac{r}{R}$
- Fireball radius+radial flow constraints dN_{ch}/dy and dE_T/dy
- Minijet Distribution (p_T> 2 GeV) NO QUENCHING

p+p @ 5 TeV

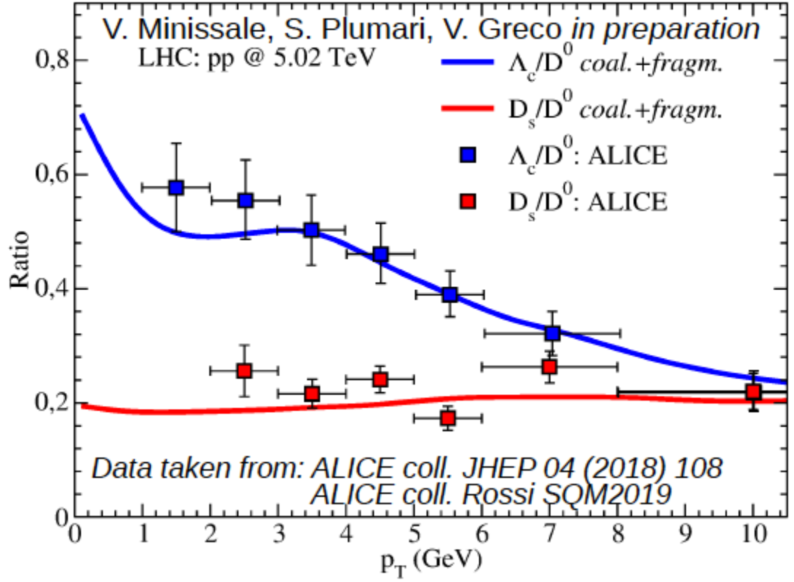
- t_{pp}=1.7 fm/c
- β_0=0.4
- R=2.5 fm
- V~30 fm^3

Hydro simulation

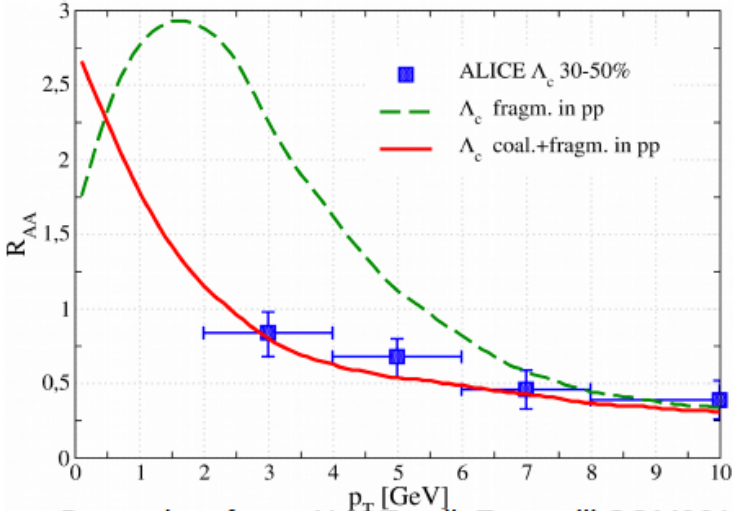
wave function widths σ_p of baryon and mesons kept the same at RHIC and LHC!

In-medium coalescence in pp

No peak in Λ_c / D^0 ratio (pp collision)



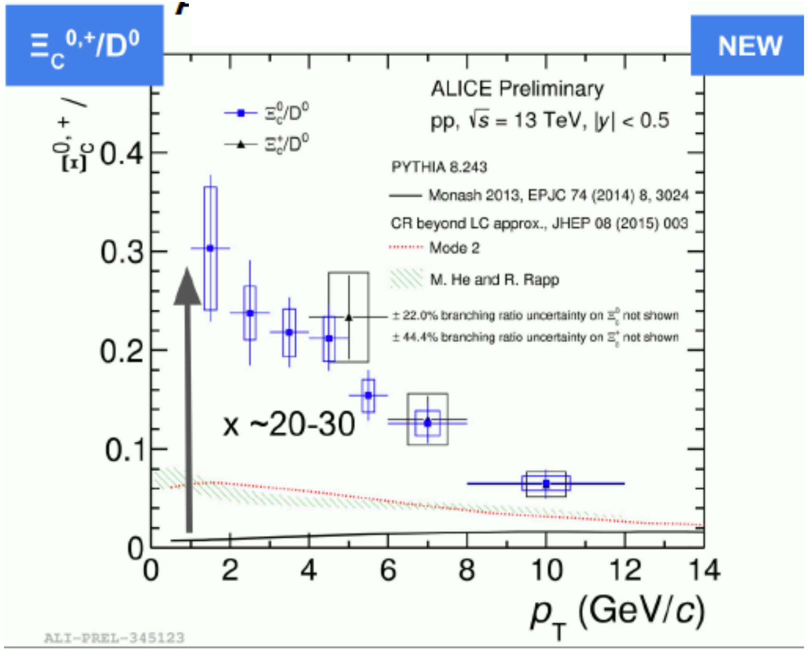
Data seem to favour model where both coalescence and fragmentation are present in pp



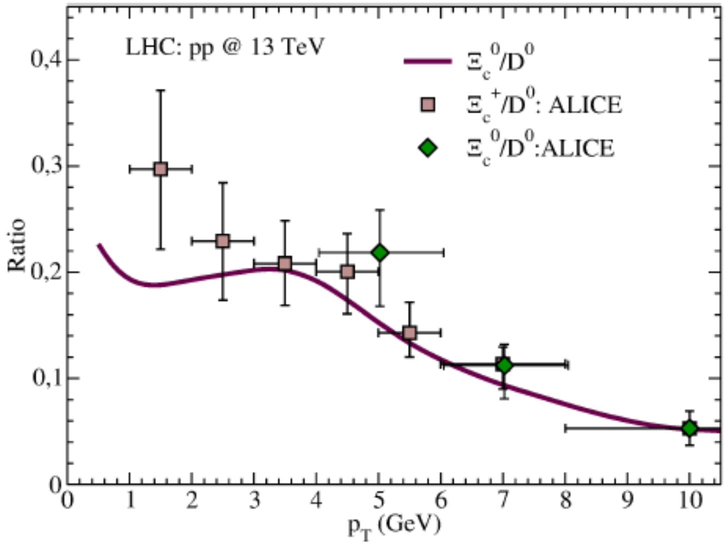
Data taken from: ALICE coll. Zampolli SQM2019

Different hadronization model affects the determination of the HQ transp. Coeff.

Heavy Baryon hadronization in pp@LHC: internal chemistry



V. Minissale, S. Plumari, V. Greco *in preparation*



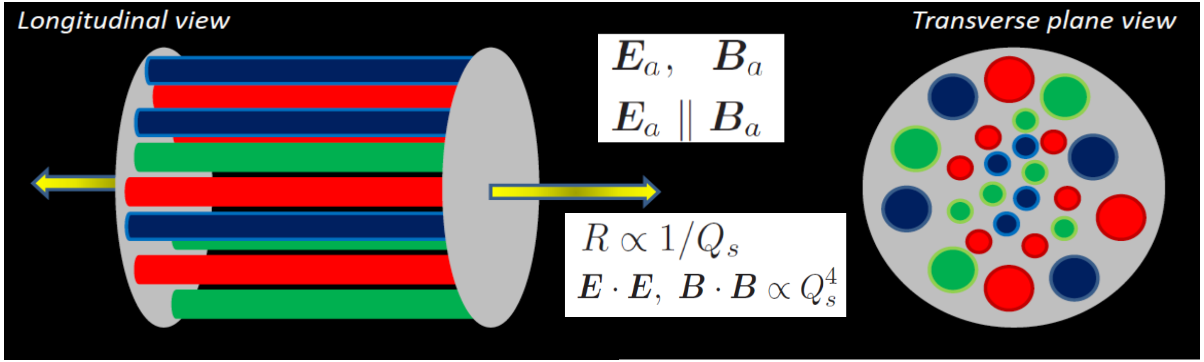
Several ratio of multi charm hadrons where the effect of enhancement are huge

At high eenergy we will see sign of such an enhancements?

Extension to Ω_{ccc} and Ξ_{cc}….

What will be able to see EIC?

A first study of HQ in a Glasma



Inizialization by MV model, PRD49 (1994)

$$\langle \rho_A^a(\boldsymbol{x}_T)\rho_A^b(\boldsymbol{y}_T)\rangle = (g^2\mu_A)^2\delta^{ab}\delta^{(2)}(\boldsymbol{x}_T - \boldsymbol{y}_T),$$

Solving classical Yang-Mills

$$E^i = \tau\partial_\tau A_i, \qquad \partial_\tau E^i = \frac{1}{\tau}D_\eta F_{\eta i} + \tau D_j F_{ji},$$

$$E^\eta = \frac{1}{\tau}\partial_\tau A_\eta, \qquad \partial_\tau E^\eta = \frac{1}{\tau}D_j F_{j\eta}.$$

Solved in SU(2)

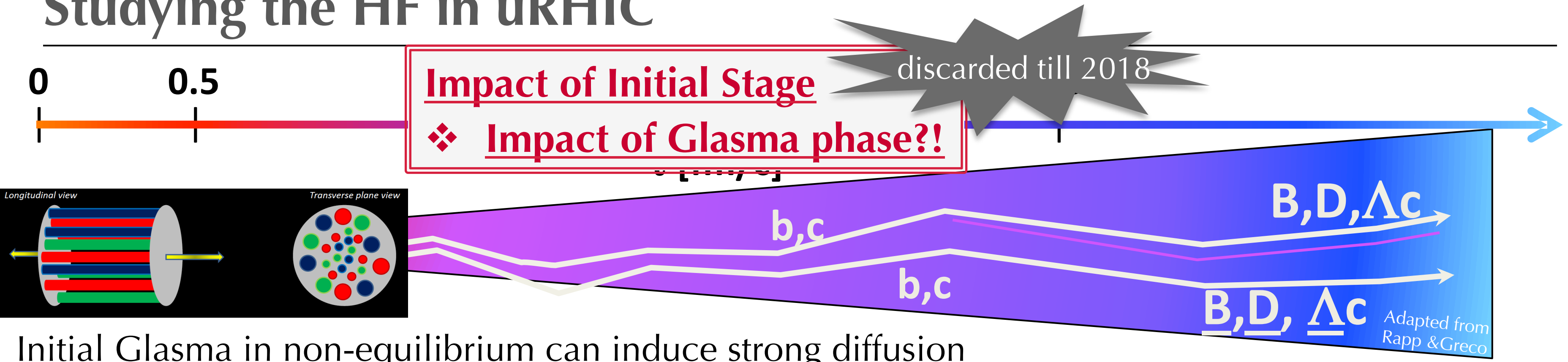
Heavy quark in the chromo magnetic field

$$\frac{dx_i}{dt} = \frac{p_i}{E},$$

$$E\frac{dp_i}{dt} = Q_a F^a_{i\nu}p^\nu,$$

$$E\frac{dQ_a}{dt} = -Q_c\varepsilon^{cba}\boldsymbol{A}_b\cdot\boldsymbol{p},$$

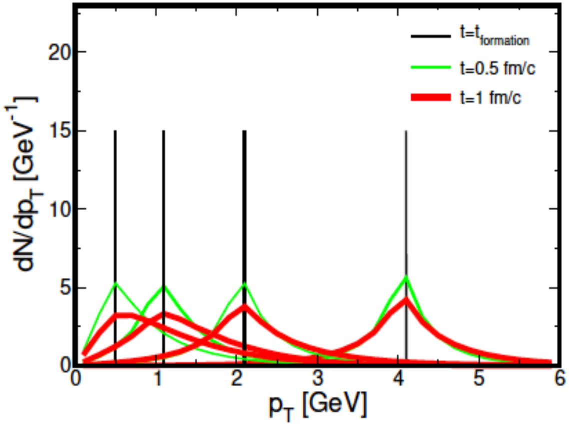
Studying the HF in uRHIC



Initial Glasma in non-equilibrium can induce strong diffusion

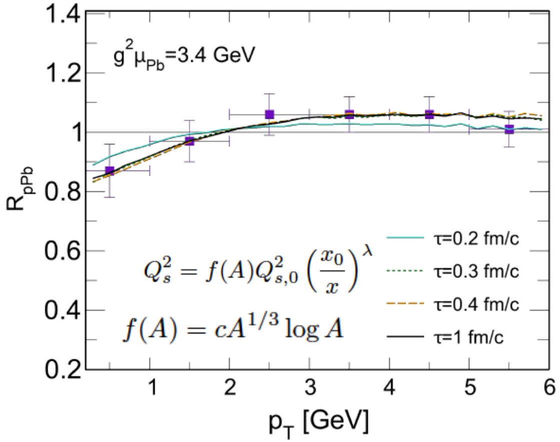
- M.Ruggieri and S.K. Das, PRD98 (2018)

Strong diffusion (box)

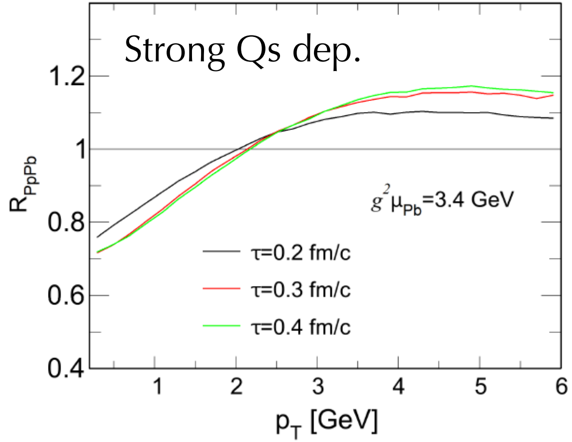


J.H.Liu et al., PRC 102(2020)

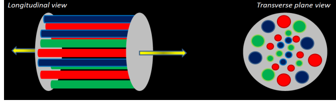
pPb@ 5.02TeV



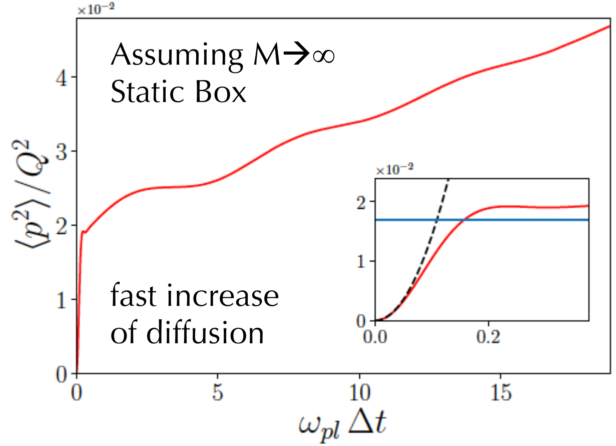
PbPb@5.02ATeV

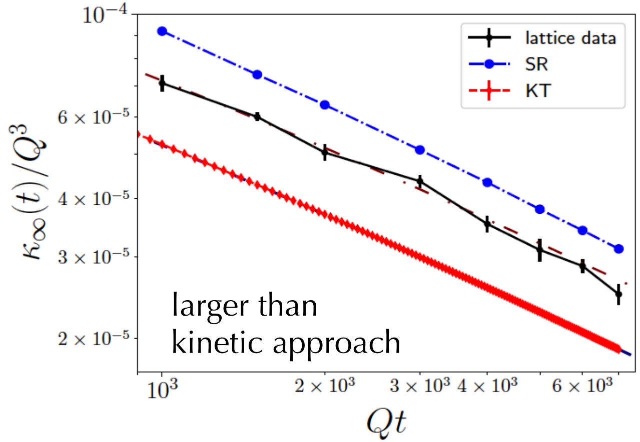


Impact of Glasma on HQ



K. Boguslavski, A. Kurkela, T. Lappi and J. Peuron, JHEP09 (2020)077 SU(3)



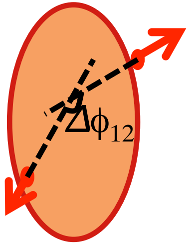


Correlator method $\langle \dot{p}_i(t)\dot{p}_i(t')\rangle = \frac{g^2}{2N_c}\langle E_i^a(t)E_i^a(t')\rangle$ $\quad 3\kappa(t,\Delta t) \equiv \frac{\mathrm{d}}{\mathrm{d}\Delta t}\langle p^2(t,\Delta t)\rangle$

Link pA <-> AA [<-> eA@EIC?]

-> May have key role for D-D angular correlation

- Any effect of glasma dynamics on HF at EIC?
- EIC can determine more precisely the QS scale



Not only suppr./enhanc.
but also angular diffusion

Conclusions ? … Summary

- **Standard Open HF physics in uRHICs:**
  - * from R_{AA} ,v_2 → **D_s(T) of Hot QCD medium ≈ lattice QCD [non-perturbative dynamics]**
  - * **Dominance of radiative Eloss (jet quenching) at p_T> 10 GeV** (SCET, DGLV, ….)
  - * **Shadowing and Qs Glasma** scale need a more precise determination → **EIC**
  - * more precision data + p→0, additional observables + **extension to b** quark will allow significant advancements and more direct comparison to lQCD

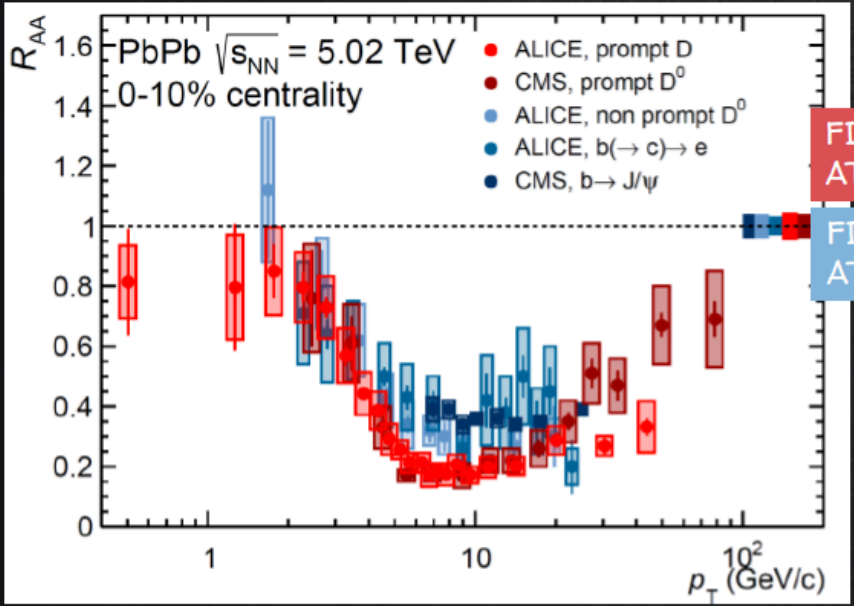
- SCET prediction for R_{eA} at EIC: specific enahncement at moderate-small z

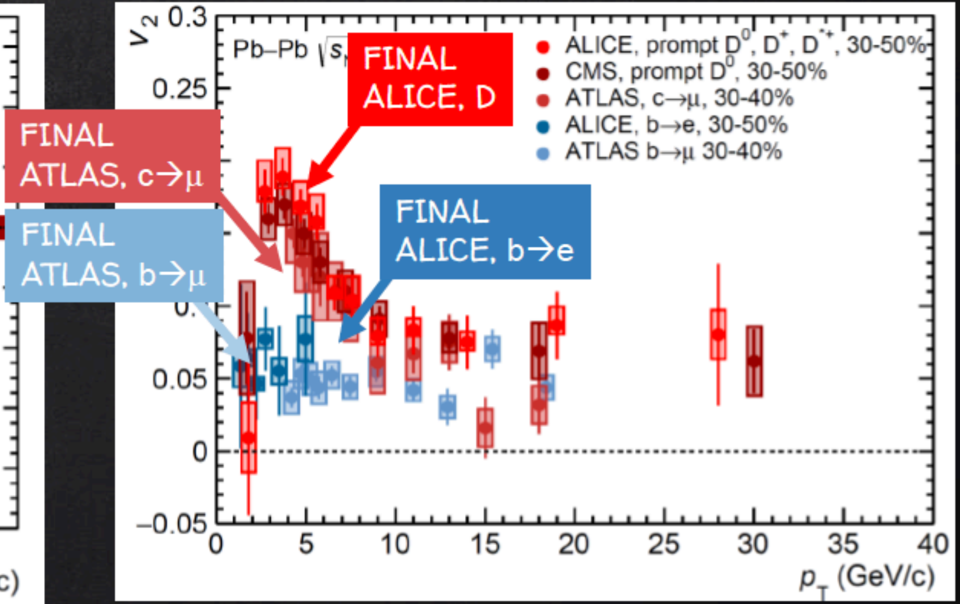
- **Hadronization and universality of FFs in HQ sector** (especially for heavy baryon)… **EIC?**

- **HF can play a role in spotting Glasma dynamics, linking pA and eA**

Back-up Slide

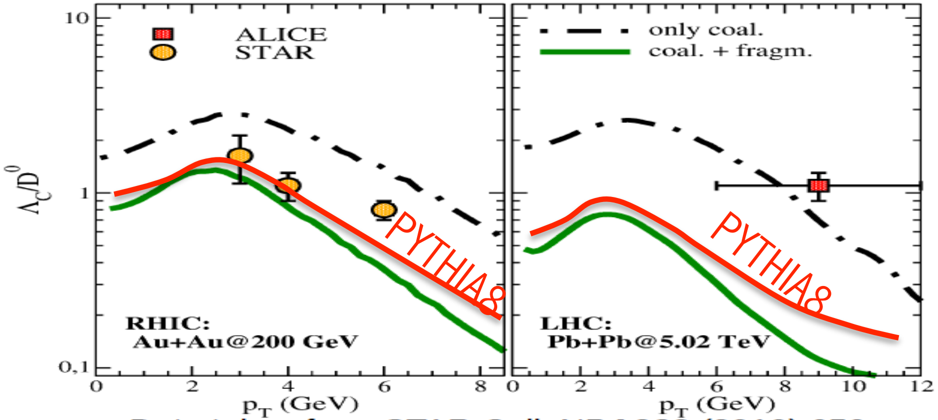
CHARM & BEAUTY





Impact of large Λ_c production on $R_{AA}(p_T)$

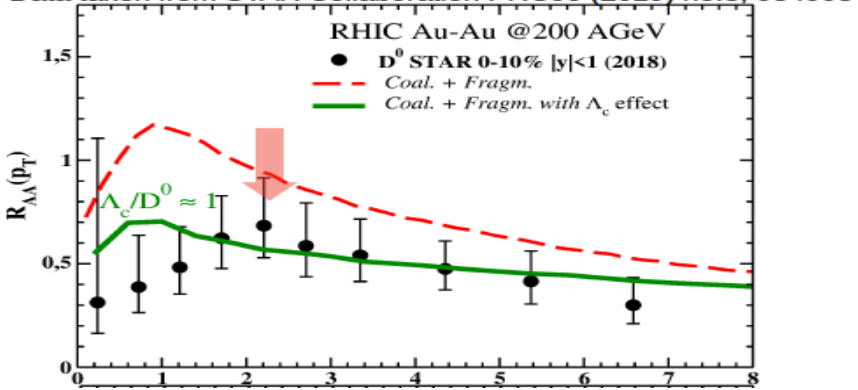
- **With the same coalescence plus fragmentation model we describe the Λ_c/D^0** S. Plumari, V. Minissale, S.K. Das, G. Coci, V. Greco, EPJ **C78** (2018) no.4, 348

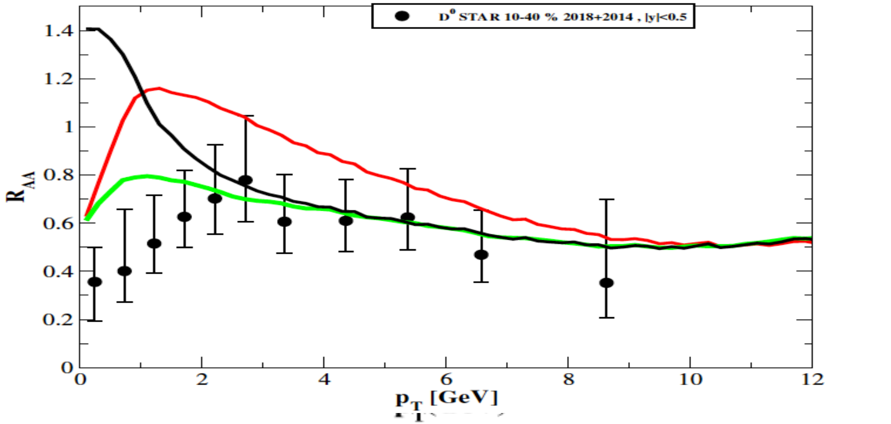


Data taken from STAR Coll. NP**A982** (2019) 659.

ALICE Coll. PL**B793** (2019) 212.

Data taken from STAR Collaboration PR**C99** (2019) no.3, 034908





S. Plumari et al., EPJ C (2018)348

✧ This open **<u>a new paradigma</u>** in studying HF in the low p_T region

RHIC: Baryon/meson

*S. Plumari, et al., Eur. Phys. J. **C78** no. 4, (2018) 348*

Coalescence

Following: L.W.Chen, C.M. Ko, W. Liu, M. Nielsen, PRC 76, 014906 (2007). K.-J. Sun, L.-W. Chen, PRC 95, 044905 (2017).
For hypersurface of proper time τ and non relativistic limit:

for $p_T << m$

$$\frac{\Lambda_c^+}{D^0} \propto \frac{g_\Lambda}{g_D}\left(\frac{m_T^\Lambda}{m_T^D}\right) e^{-(m^\Lambda - m^D)/T_c} \; \tau \mu_2$$

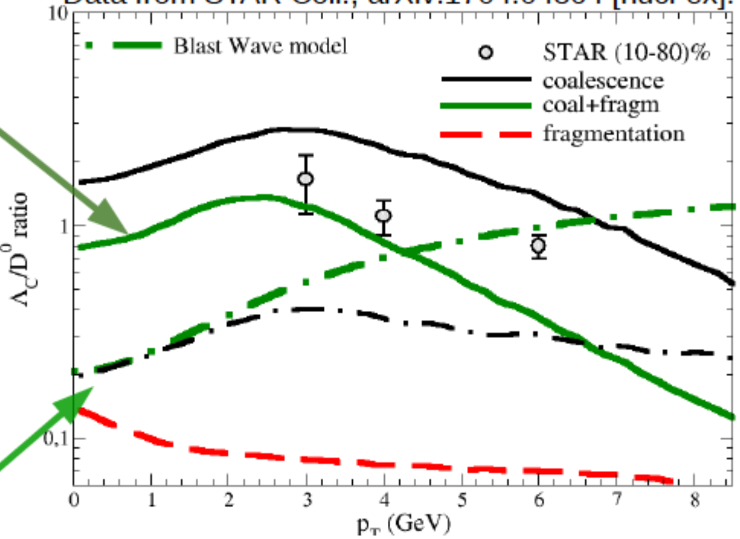
$$\mu_2 = \frac{m_3(m_1+m_2)}{m_1+m_2+m_3}$$ Is the reduced mass of the baryon

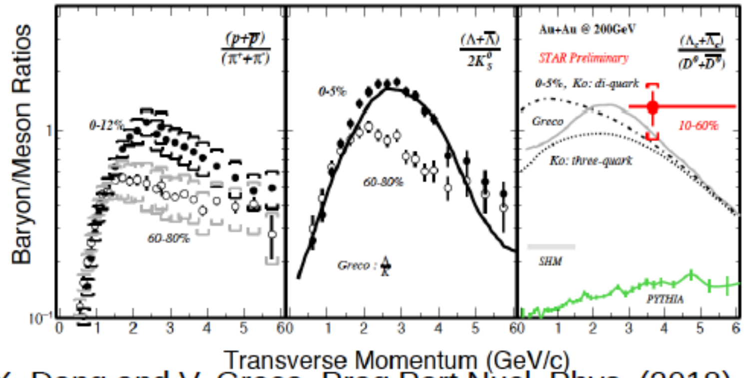
Blast Wave model:

$$\frac{\Lambda_c^+}{D^0} = \frac{g_\Lambda}{g_D}\frac{m_T^\Lambda}{m_T^D}\frac{K_1(m_T^\Lambda/T_C)}{K_1(m_T^D/T_C)}$$

for $p_T << m$ $$\approx \frac{g_\Lambda}{g_D}\left(\frac{m_T^\Lambda}{m_T^D}\right)^{1/2} e^{-(m^\Lambda - m^D)/T_c} \approx 0.17$$

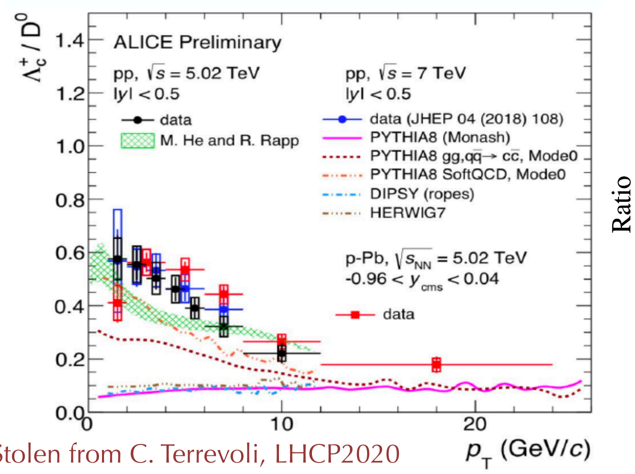
Data from STAR Coll., arXiv:1704.04364 [nucl-ex].



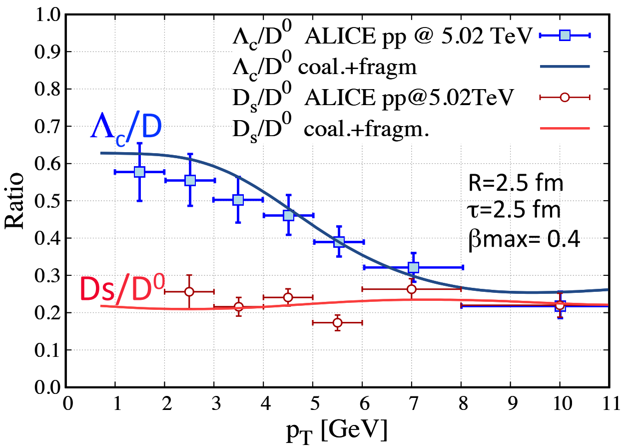


X. Dong and V. Greco.,Prog.Part.Nucl. Phys. (2018)

Heavy Baryon hadronization Λ_c in pp



Stolen from C. Terrevoli, LHCP2020



Same Coalescence+fragm as for AA

assuming a pp hydro fireball

M. Habich et al., EPJ. C76 (2016)

naturally explain the ratio in pp:
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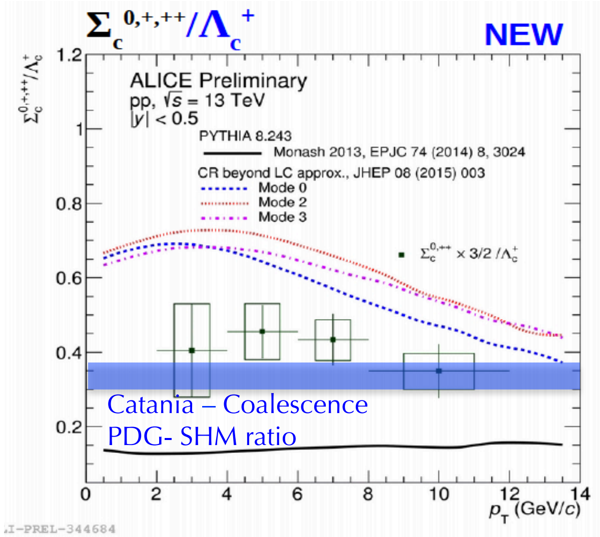

- ❖ **Possibility to have a coherent hadronization scheme from pp to AA**

  - New CR can also describe it in pp

  but there is much more to study:

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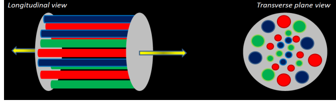
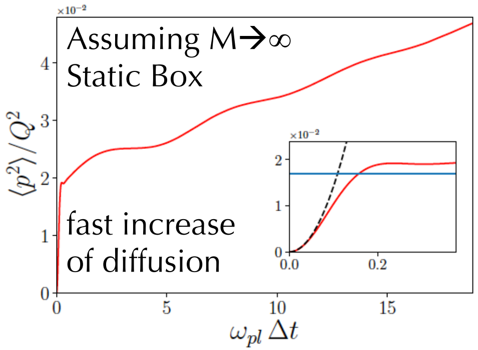
  - vs ***internal chemistry***, resonance feedown

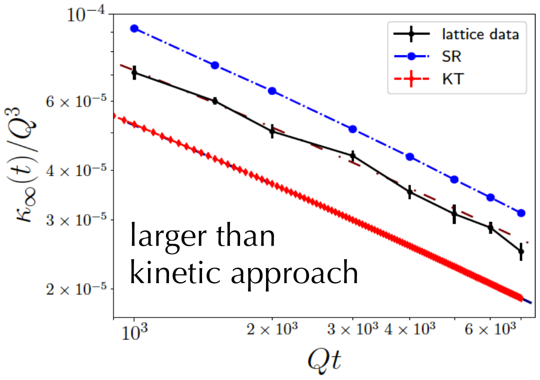
C.Hills, Wed 10.30

Impact of Glasma on HQ



K. Boguslavski, A. Kurkela, T. Lappi and J. Peuron, arXiv:2005.02418





Correlator method

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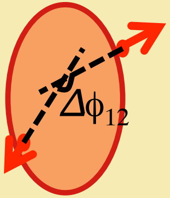
Link pA <-> AA

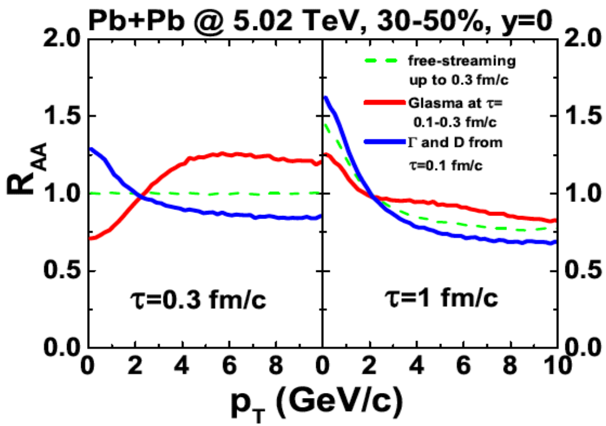
Using HQ as a probe of the Glasma

-> May have key role for

D-D angular correlation



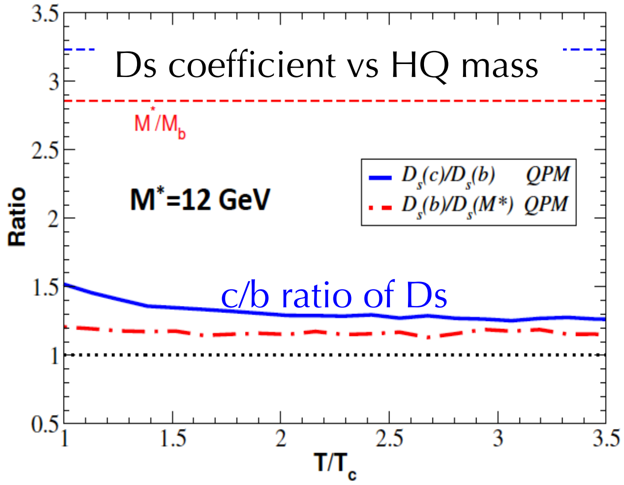
Impact on AA collisions observables (interacting at $\tau=\tau_{form}$)



- Dominance of diffusion-like
  → **enhancement of $R_{AA}(p_T)$**
- **Gain in v_2**: larger interaction
  in QGP stage to have same $R_{AA}(p_T)$

Y. Sun et al., PLB 798 (2019)

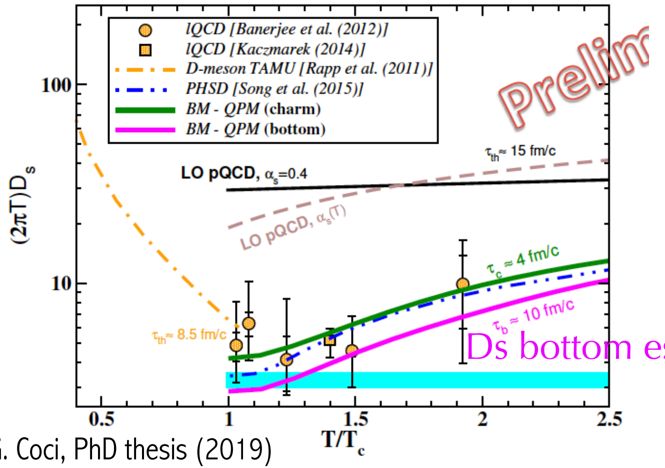
What changes from c to b ? Large mass limit?



Kinetic th. (same interact.): $\tau_{th}(b)/\tau_{th}(c) \approx \gamma_b/\gamma_c \approx M_b/M_c$ and $D_S = \frac{T}{M\gamma} = \frac{T}{M}\tau_{th}$

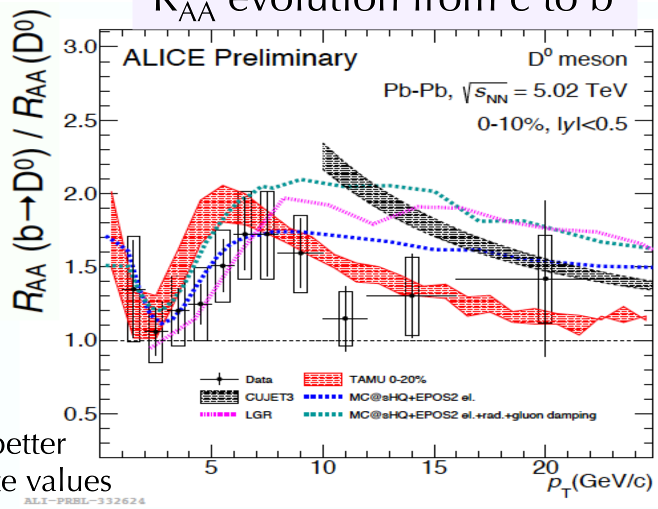
→ D_s ideally M indipendent ($M \to \infty$)

- ✧ D_s in QPM approach is 30-40% smaller for bottom
- ✧ $M \to \infty$ limit is not reached for charm
- ✧ Start having similar plots from all the models…



G. Coci, PhD thesis (2019)

R_{AA} evolution from c to b



TAMU w/o rad. E_{loss}- better likely miss the absolute values

Relativistic Boltzmann at finite η/s

$$p^\mu \partial_\mu f_q(x,p) + m(x)\,\partial^x_\mu m(x)\,\partial^\mu_p f_q(x,p) = C[f_q, f_g]$$
$$p^\mu \partial_\mu f_g(x,p) + m(x)\,\partial^x_\mu m(x)\,\partial^\mu_p f_g(x,p) = C[f_q, f_g]$$

Equivalent to viscous hydro $\eta \backslash s \approx 0.1$

free streaming   Interaction $\varepsilon - 3p \neq 0$ C[f] gauged to some $\eta/s \neq 0$

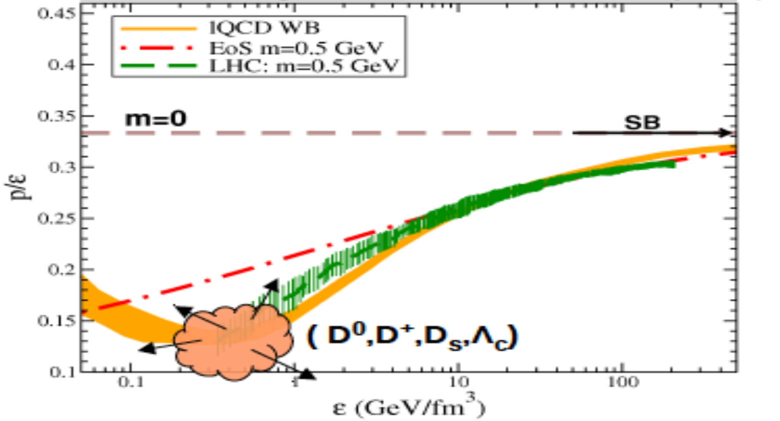
Heavy Quarks evolution

$$p^\mu \partial_\mu f_Q(x,p) = \mathcal{C}[f_q, f_g, f_Q](x,p)$$

$$\mathcal{C}[f_Q] = \frac{1}{2E_1}\int \frac{d^3p_2}{2E_2(2\pi)^3}\int \frac{d^3p'_1}{2E_{1'}(2\pi)^3} \times [f_Q(p'_1)f_{q,g}(p'_2) - f_Q(p_1)f_{q,g}(p_2)] \times |\mathcal{M}_{(q,g)+Q}(p_1p_2 \to p'_1p'_2)|^2 \times (2\pi)^4\delta^4(p_1 + p_2 - p'_1 - p'_2)\ ,$$

$\mathcal{M}$ scattering matrix by QPM model fit to lQCD thermodynamics

S. Plumari et al.,J.Phys.Conf.Ser. 981 012017 (2018).



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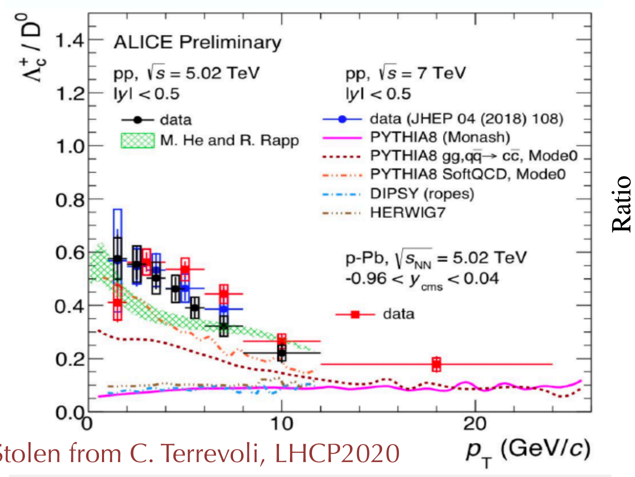

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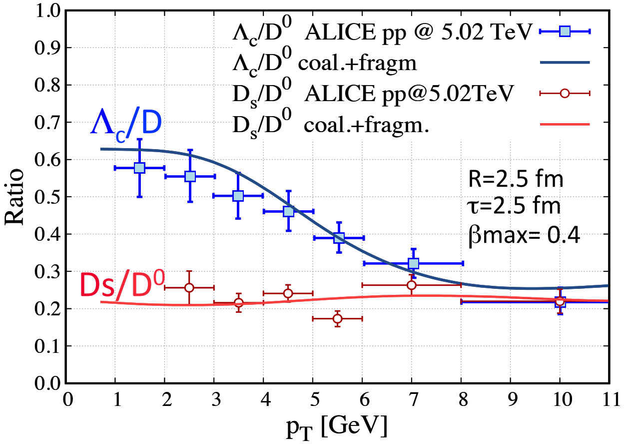

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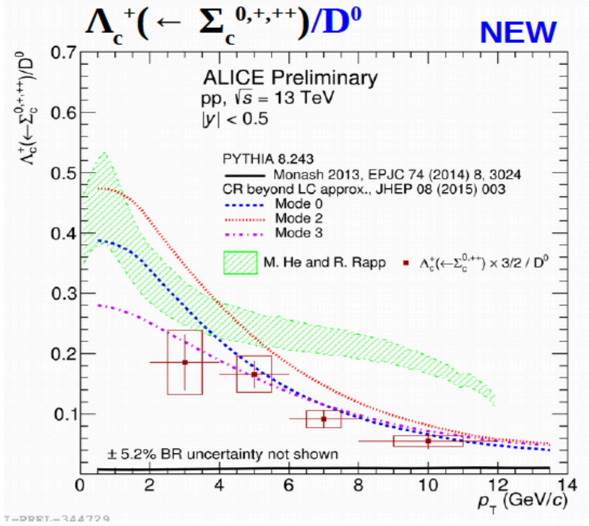

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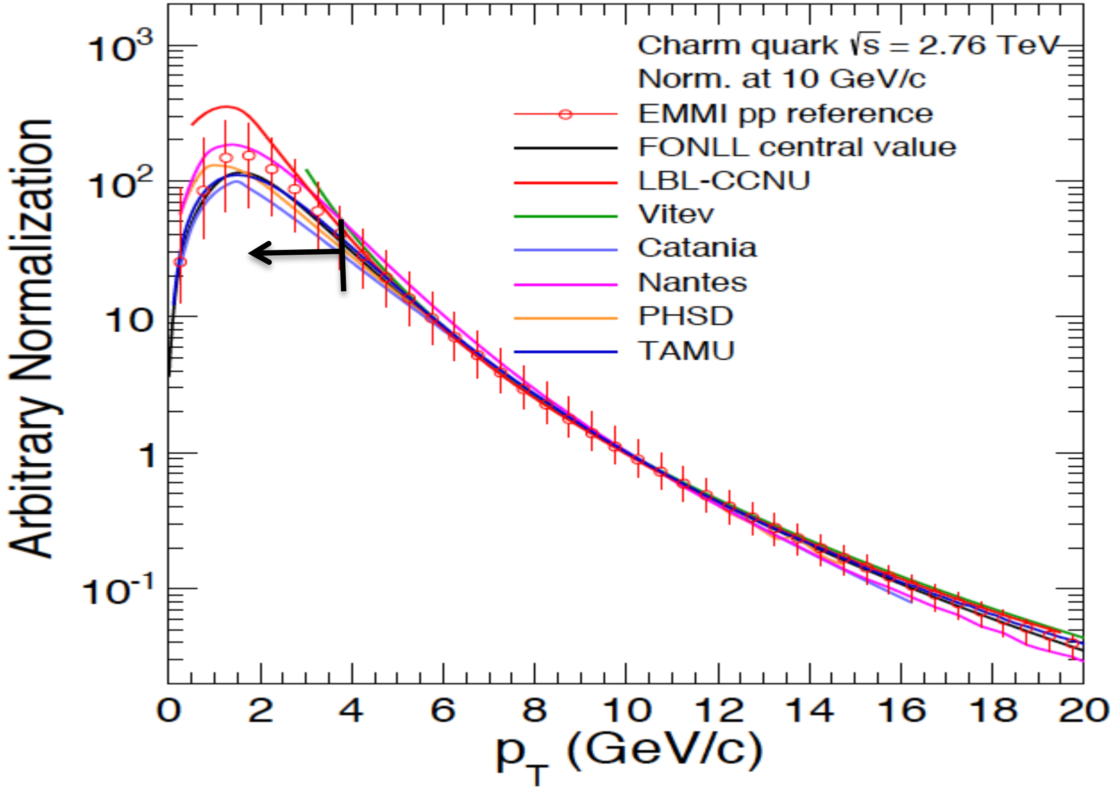
but there is much more to study:

- vs $dN_{ch}/d\eta$ with new exp. Data
- vs ***internal chemisty***, resonance feedown

C.Hills, Wed 10.30

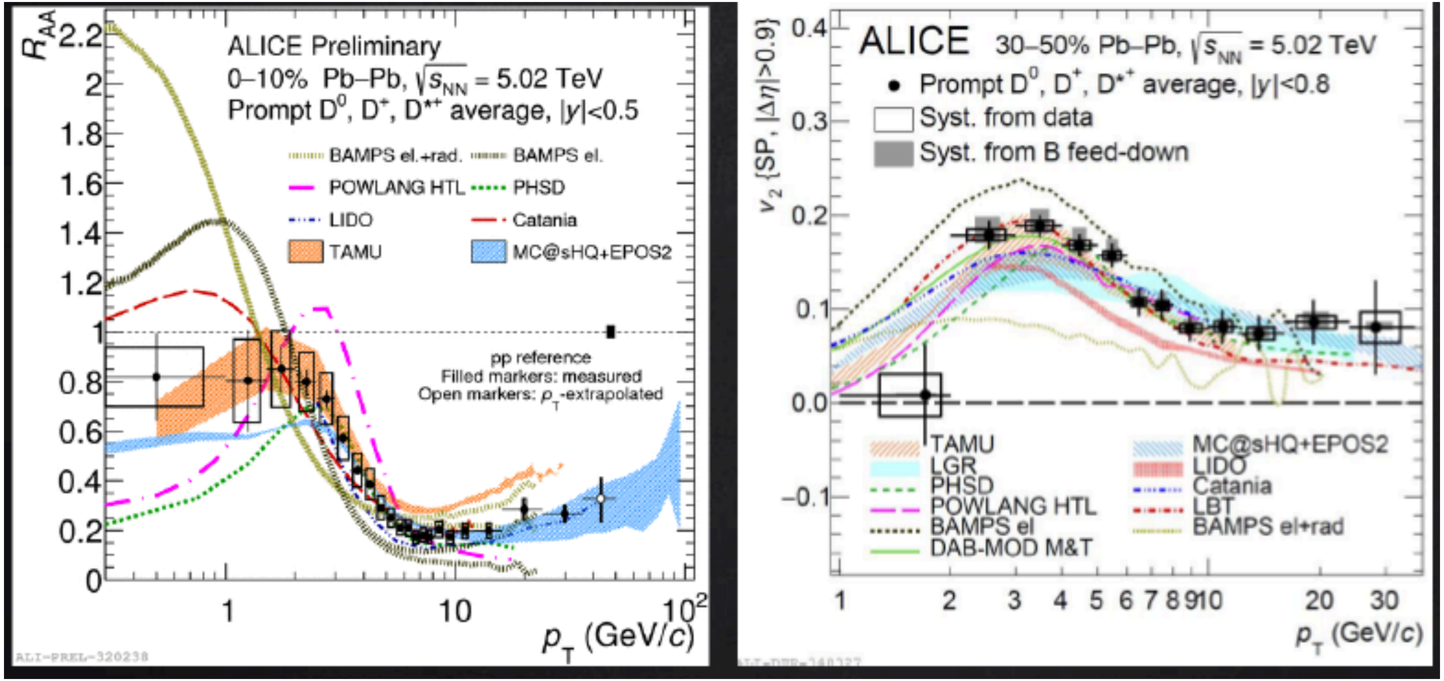
Initial Charm distribution from various groups

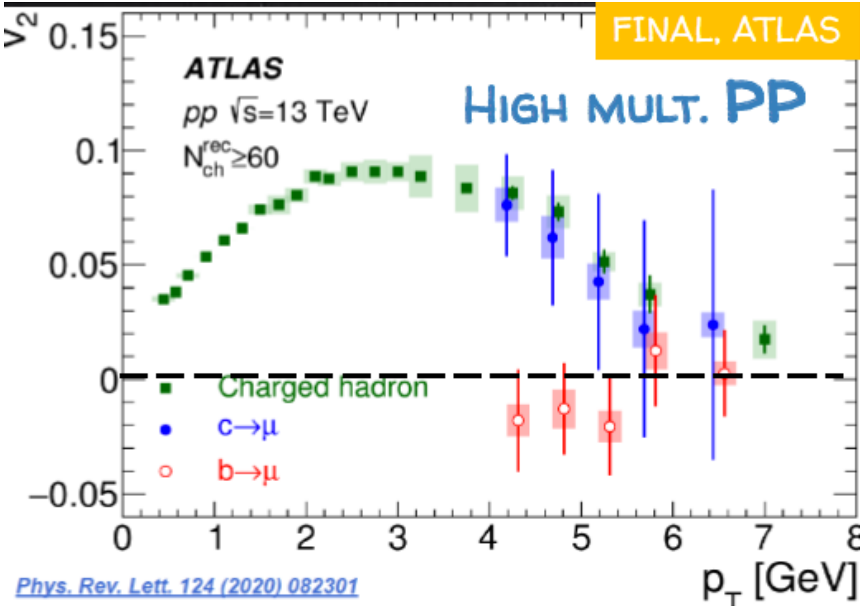


EMMI-RRTF Collab., ArXiV:1803.03824
NPA979(2018)

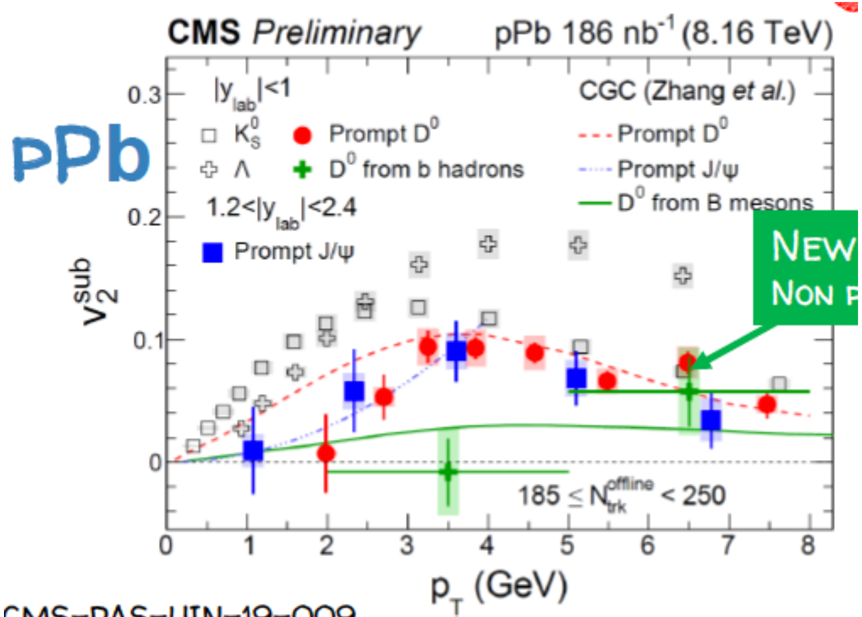
Still to our purpose (R_{AA} at p_T< 4-5 GeV)

The best would be good precision data at low p_T


ALICE Preliminary
0–10% Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Prompt D^0, D$^+$, D^{*+} average, |y|<0.5
BAMPS el.+rad.
BAMPS el.
POWLANG HTL
PHSD
LIDO
Catania
TAMU
MC@sHQ+EPOS2
pp reference
Filled markers: measured
Open markers: p_T-extrapolated
R_{AA}
p_T (GeV/c)
ALI-PREL-320238
ALICE 30–50% Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Prompt D^0, D$^+$, D^{*+} average, |y|<0.8
Syst. from data
Syst. from B feed-down
TAMU
LGR
PHSD
POWLANG HTL
BAMPS el
DAB-MOD M&T
MC@sHQ+EPOS2
LIDO
Catania
LBT
BAMPS el+rad
v_2 {SP, |Δη|>0.9}
p_T (GeV/c)

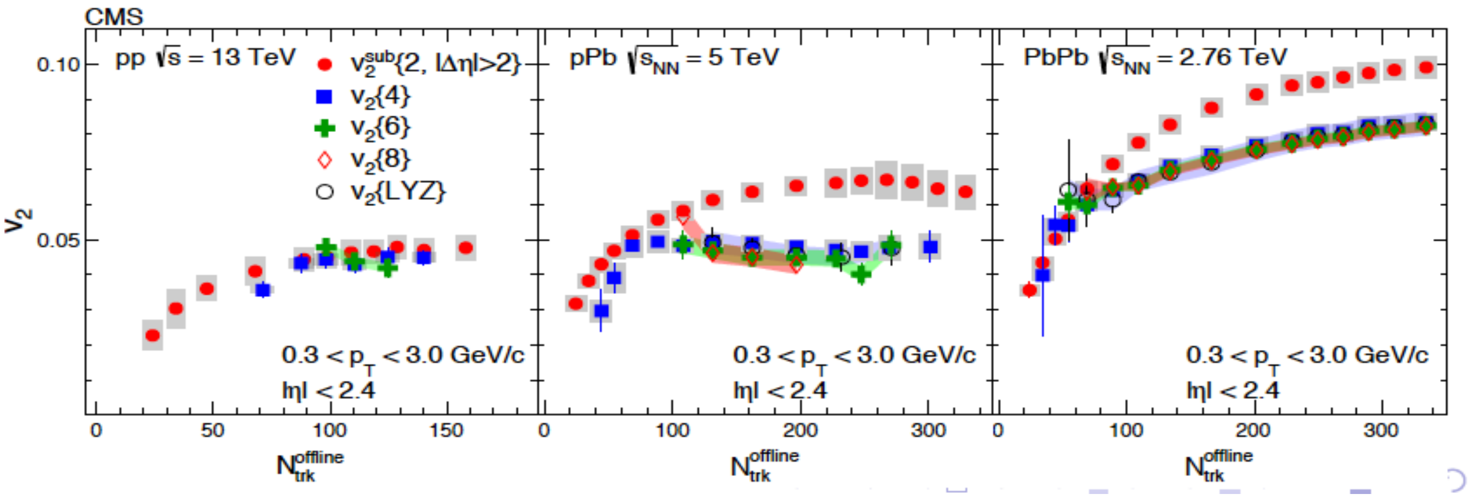


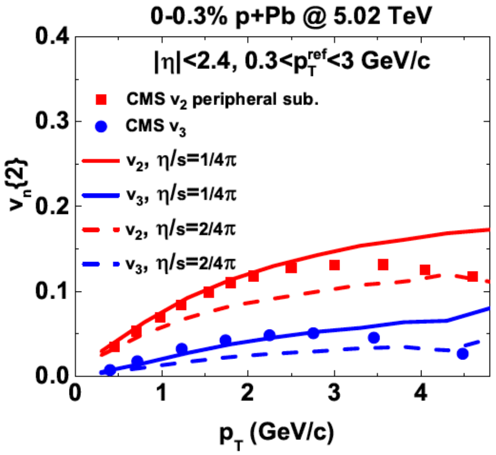
Phys. Rev. Lett. 124 (2020) 082301



CMS-PAS-HIN-19-009

Collective flow in pp, pA and AA





Prediction by a Relativistic Boltzmann approach applied to pA