Heavy-quark transport and hadronization, including multi-heavy-flavour: large & small collision systems

Vincenzo Greco –
University of Catania/INFN-LNS

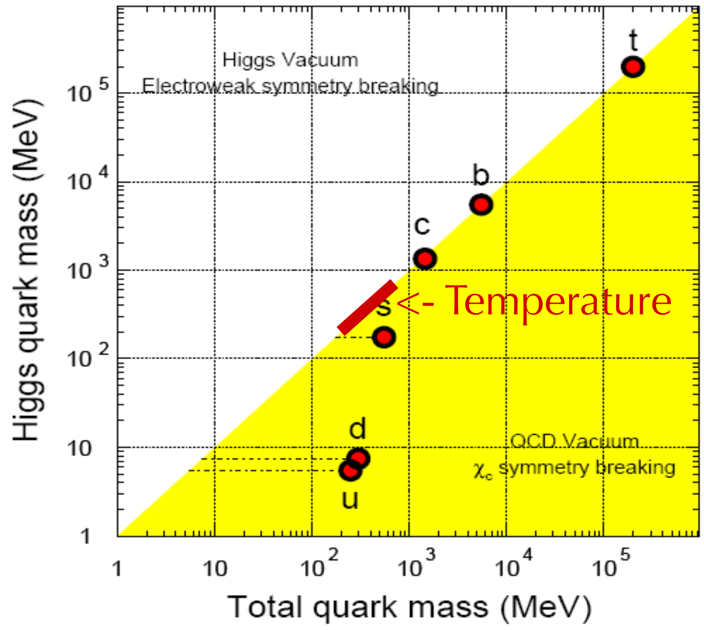
High Luminosity LHC and Hadron Colliders, LNF, Frascati, 1-4 Ottobre 2024

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA
Finanziato dall'Unione europea
NextGenerationEU

Outline

- ✧ **Basic concepts & motivation for HQ physics in HotQCD matter**
- ✧ **Results from the first stage:**
  - strong non-perturbative HQ dynamics [agreement to LQCD?!, close to AdS/CFT limit?]
  - non-universal hadronization ≠ e^+e^- in AA, but seems even in pp@TeV
- ✧ **Why precise measurement at low p_T, extension to bottom & access to new observables allow for a breakthrough**
- ✧ **The relevance of multi-charm production and scan from PbPb → OO :**

Basic Scales and specific of HQ



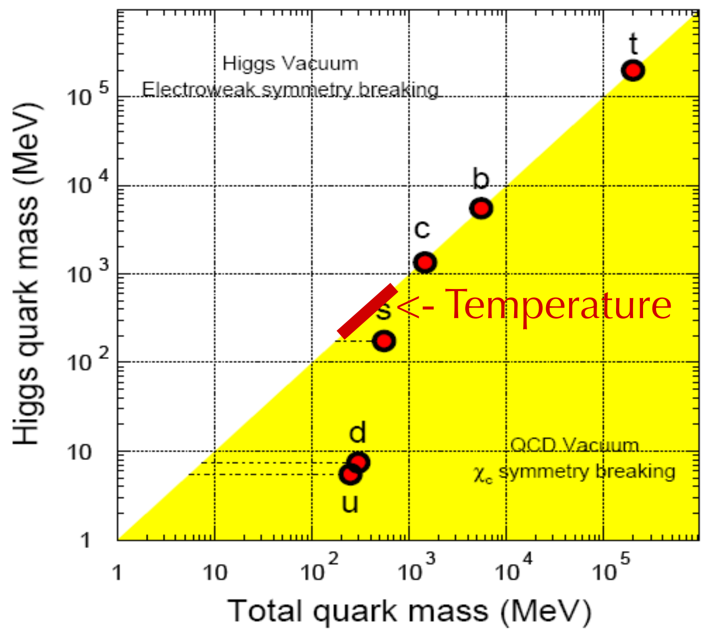
Why Heavy?

- *PARTICLE Physics*: $m_{c,b} >> \Lambda_{QCD}$ pQCD initial production
- *PLASMA Physics*:
  - $m_{c,b} >> T_{RHIC,LHC}$ no thermal production
  - $m_{c,b} >> gT_{RHIC,LHC}$ soft scatterings → Brownian motion

Specific Features:

- $\tau_0 \approx 1/2m_Q << \tau_{QGP}$ witness of all the QGP evolution
- $\tau_{th} \approx \tau_{QGP} >> \tau_{q,g}$ carry more information of their evolution

Basic Scales and specific of HQ



Why Heavy?

- *PARTICLE Physics*: $\mathbf{m_{c,b} >> \Lambda_{QCD}}$ pQCD initial production
- *PLASMA Physics*:
  - $\mathbf{m_{c,b} >> T_{RHIC,LHC}}$ no thermal production
  - $\mathbf{m_{c,b} >> gT_{RHIC,LHC}}$ soft scatterings → Brownian motion

Specific Features:

- $\tau_0 \approx 1/2m_Q << \tau_{QGP}$ witness of all the QGP evolution
- $\tau_{th} \approx \tau_{QGP} >> \tau_{q,g}$ carry more information of their evolution

❖ For HQ we know initial p_T distribution at variance with light quark & gluons

❖ HQ not created at hadronization $\mathbf{m_{b,c} >> \Lambda_{QCD}, T}$:

HQ link to Lattice QCD at finite T

❖ Ab-initio Diffusion Transport Coefficient

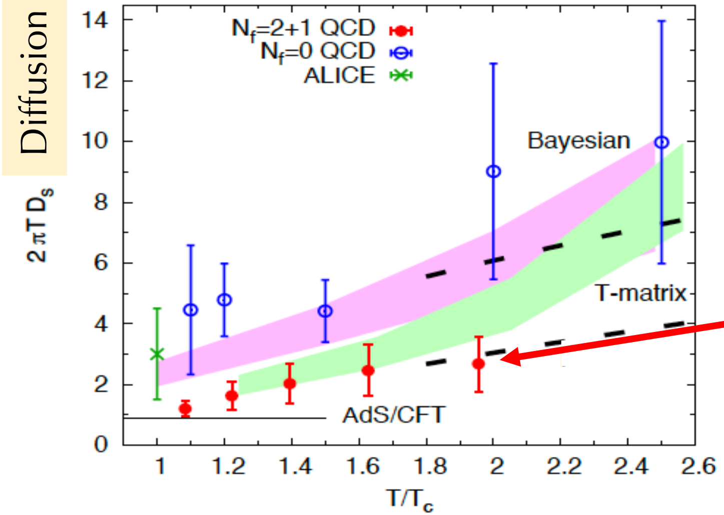
Spectral function ρ_E extracted **from euclidean color-electric correlator** $D_E(\tau)$ →

Kubo formula diffusion in the p→0 limit:

$$\frac{D_p}{T^3} = \lim_{\omega\to 0} \frac{T\rho_E(\omega)}{\omega} \longrightarrow D_s = \frac{T^2}{D_p} = \frac{T}{M_Q}\tau_{th}$$

D_s determines diffusion (brownian limit) and by fluctuation-dissipation theorem:
HQ momentum drag γ → thermalization time

L. Altenkort et al., PRL131 (2023)



$\langle p \rangle = p_0 e^{-\gamma t}$ $\quad \langle \Delta p^2 \rangle = 3D_p/\gamma(1-e^{-2\gamma t})$ $\quad D_s = \frac{T}{M\gamma} = \frac{T^2}{D_p} = \frac{T}{M}\tau_{th}$

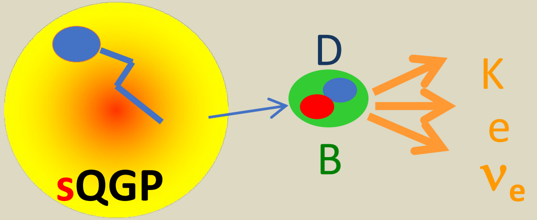
Approximations/limitations:

- *Extraction of* $\rho_E(\omega)$ from $D_E(\tau)$ is not a well posed problema with *a finite limited # of points*
- *infinite HQ massvs. charm quark, continuum extrapolation…*
- *quenched* $N_f=0$ → *to non quenched QCD (2023-24)*

HQ allow for developing a NRQCD EFT at finite T
& many-body T-matrix from V(r,T) by LQCD

Standard Dynamics of Heavy Quarks in the QGP

c,b quarks



Brownian Motion limit

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

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

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

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

$D_p = ET\gamma$ – Fluct. Diss. Theor.

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

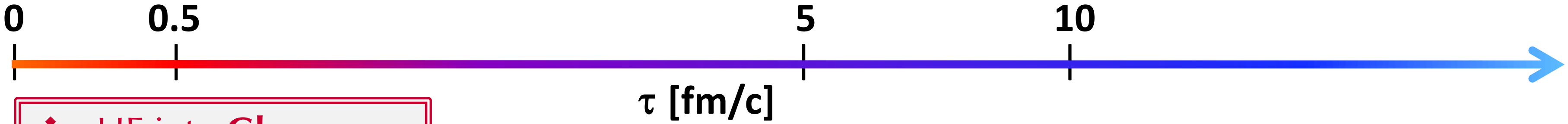
$$D = \frac{1}{2} \int d^3k |M(k,p)|^2 p^2$$

$|\mathcal{M}|^2$ scatt. matrix from: HTL, pQCD coll., rad., T-matrix, QPM, NREFT, AdS/CFT…

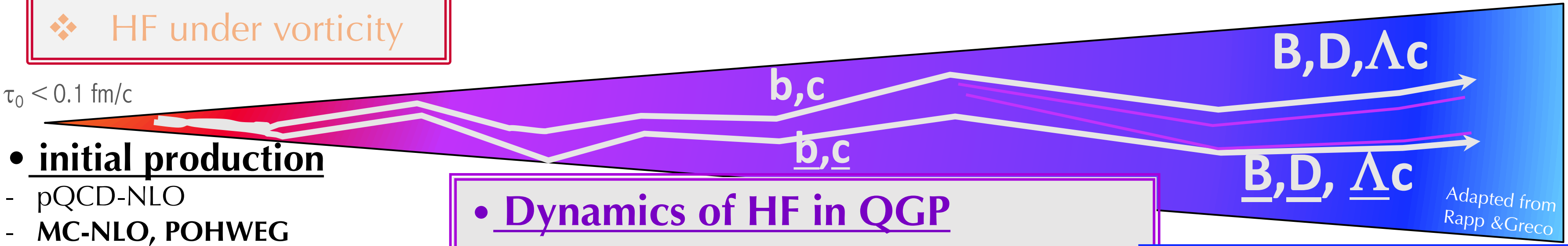
$$D_S = \frac{T}{M\gamma} = \frac{T^2}{D_p} = \frac{T}{M}\tau_{th}$$

- This is the main set up at least at $p < 8$-10 GeV
- Brownian motion challenged for charm ($M_c \sim 3\,T \sim gT$): Relativistic Boltzmann dynamics
- At $p_T > 10$ GeV radiative E_{loss} , q_{hat}, jet physics [Cunqueiro Mendez, previous talk]

Studying the HF in uRHIC

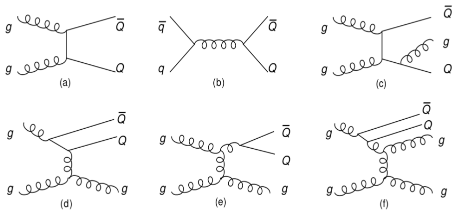


- ❖ HF into **Glasma**
- ❖ HF under **e.m. field**
- ❖ HF under vorticity



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

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



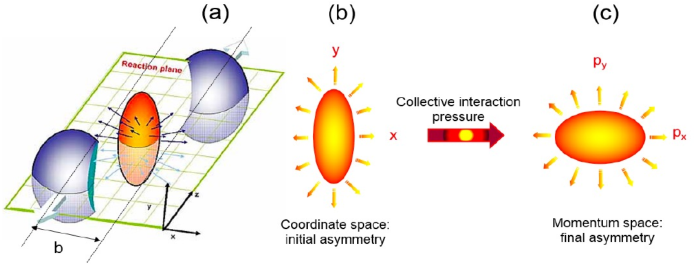
- **Dynamics of HF in QGP**
  - **Themalization**
  - **Transp. Coeff. of QCD matter $D_s(T)$**
  - Radiative E_{loss} & Jet Quenching

- **Hadronization**
  - coalescence and/or fragm.
  - large Λ_c/D in pp,pA,AA
  - → Affects $R_{AA}(p_T)$, $v_2\ (p_T)$

$M_c \sim 1.5$ GeV, $m_q \sim 0.01$ GeV but in-medium strong interaction
Makes charm it nearly part of the QGP bulk fluid

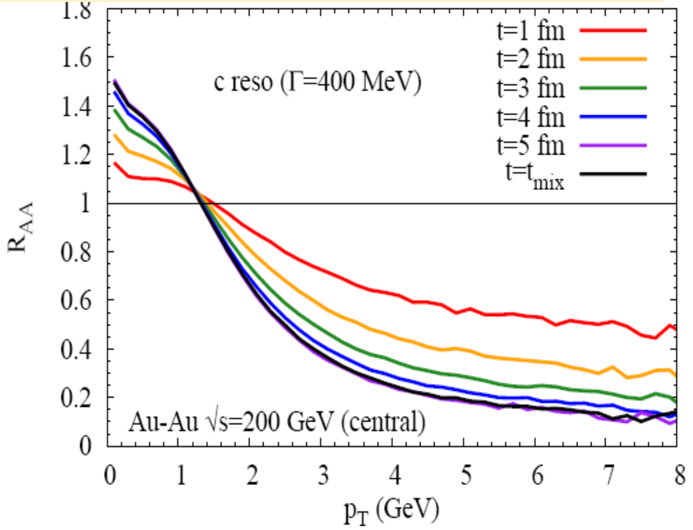
R_{AA} and v_2 evolution & correlation

No interaction means R_{AA}=1 and v_2=0.
more interaction decrease R_{AA} and increase v_2

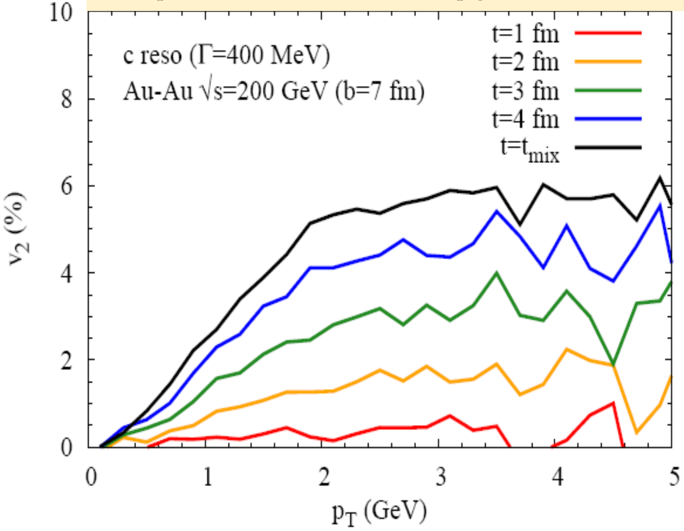


R_{AA} is "generated" faster than v_2

R_{AA} Ratio normalized p_T spectra pp/AA



Elliptic Flow:Anisotropy Azimuthal emission

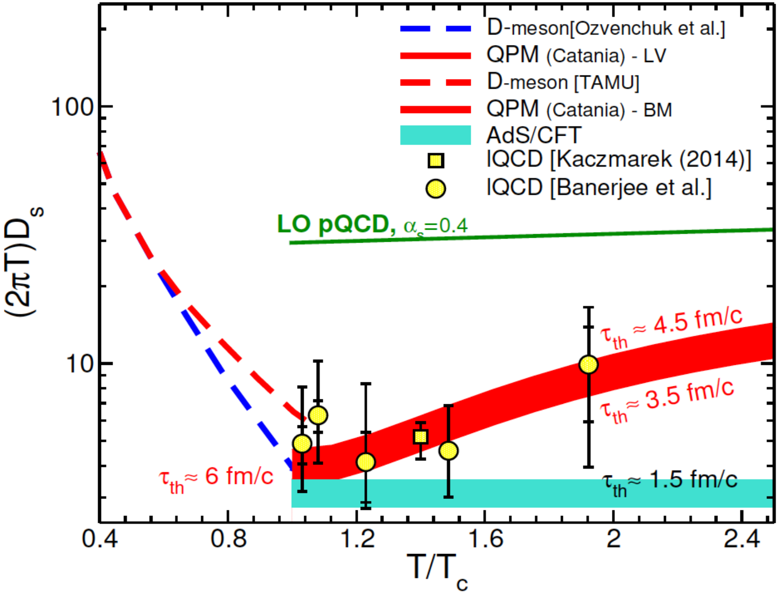


v_2 formation time ~ R
+
for HQ come from
The drag of QGP fluid

The relation between R_{AA} and time is **not trivial** and depend on the time (temperature) dependence of the interaction.

Diffusion Coefficient of Charm Quark:first stage

uRHIC created matter is the **Hot QCD matter not in perturbative regime**!



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

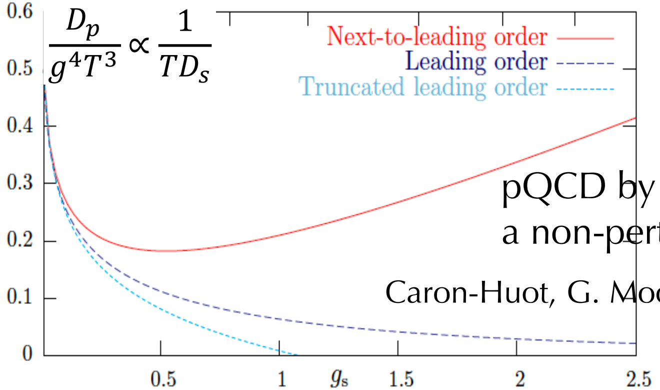
$$\tau_{th} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8 \frac{2\pi T D_s}{(T/T_c)^2} \text{ fm/c}$$

pQCD, Asymptotic free regime

Not a model fit to lQCD data!

Phenomenology R_{AA} & $v_2 \approx$ Lattice QCD

Infinite Strong Coupling (AdS/CFT)



pQCD by itself indicates a non-pert. behavior

Caron-Huot, G. Moore, JHEP(2008)

- Largely non-perturbative Ds (close AdS/CFT)

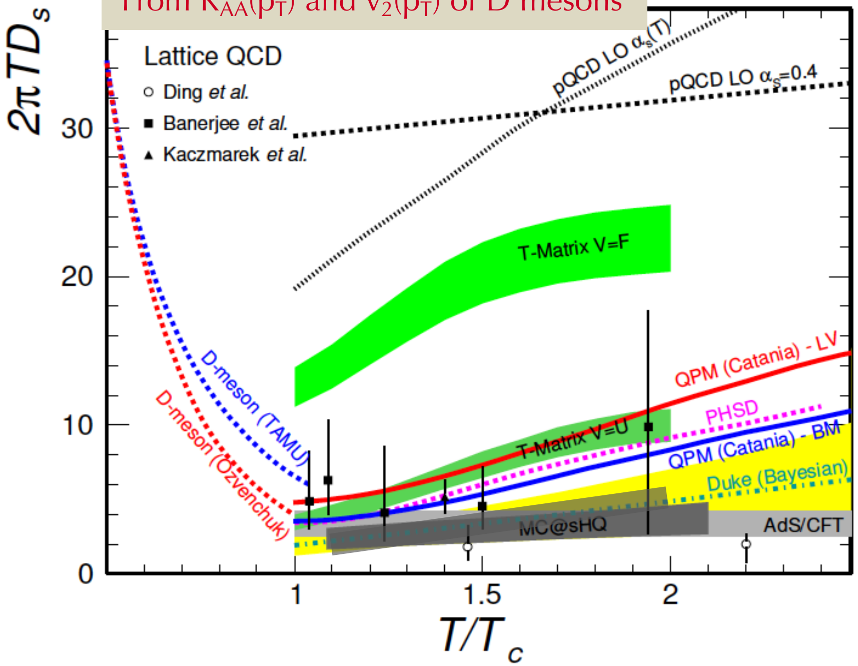
  Non perturbative interaction

  even if $M_Q >> \Lambda_{QCD}$ and $M_Q >> m_q$

Diffusion of Charm Quark: first stage

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

From $R_{AA}(p_T)$ and $v_2(p_T)$ of D mesons



$$\tau_{th} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8 \frac{2\pi T D_s}{(T/T_c)^2} \text{ fm/c} \approx$$ **4-5 fm/c** ($p \rightarrow 0$, T_c)

*Main differences in comparing to LQCD-AdS/CFT:

- quenched QCD (Yang-Mills) + $M_Q \rightarrow \infty$
- **phenomenology at intermediate p_T – LQCD(AdS/CFT) at $p \rightarrow 0$**

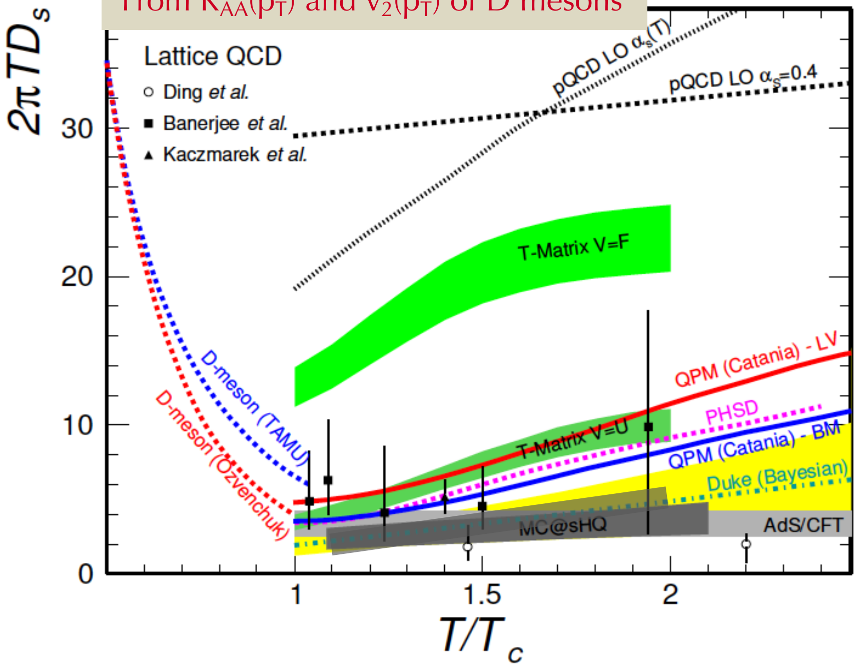
*Main sources of differences in models:

- impact of **hadronization** («unexpected» large baryon production)
- **momentum depedence of matrix elements**
- **data not enough precise/observable not enough constraining**

Diffusion of Charm Quark: first stage

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

From $R_{AA}(p_T)$ and $v_2(p_T)$ of D mesons



$$\tau_{th} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8 \frac{2\pi T D_s}{(T/T_c)^2} \text{ fm/c} \approx$$ **4-5 fm/c** ($p \to 0$, T_c)

New LQCD 2023-24 at least a factor of 2 smaller

*Main differences in comparing to LQCD-AdS/CFT:

- quenched QCD (Yang-Mills) + $M_Q \to \infty$
- **phenomenology at intermediate p_T – LQCD(AdS/CFT) at $p \to 0$**

*Main sources of differences in models:

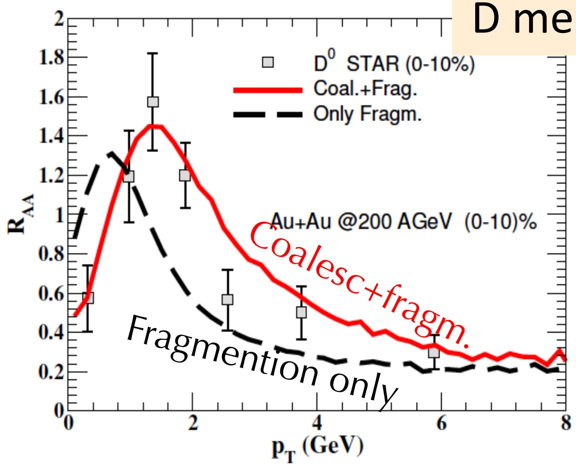
- impact of **hadronization** («unexpected» large baryon production)
- **momentum depedence of matrix elements**
- **data not enough precise/observable not enough constraining**

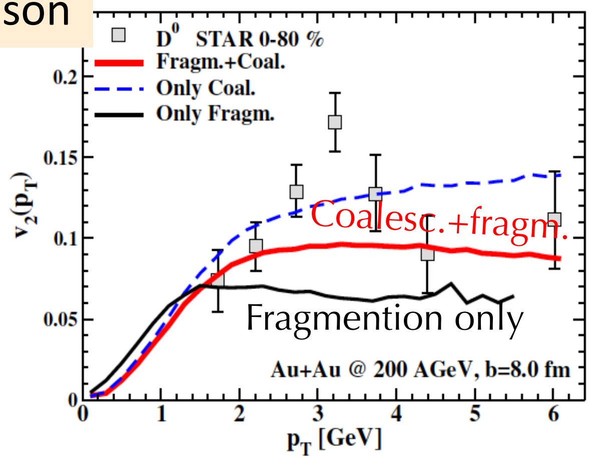
QGP diffuse Charm quarks like a "perfect fluid"

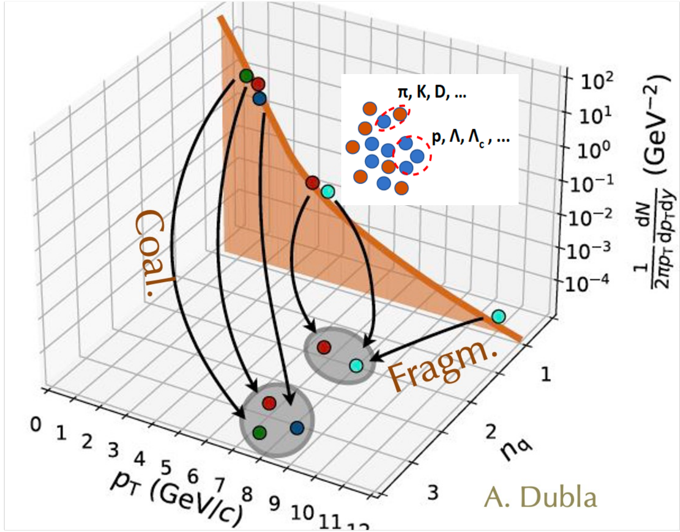
	Matter State	D_s (cm^2/s)
Air in Water	liquid	2.0×10^{-5}
Hydrogen in Iron	solid	1.66×10^{-9}
HQ in QGP	Liquid?	$(100\text{-}500) \times 10^{-5}$

Impact of HF in-medium Hadronization

D meson







- <u>Opposite</u> to in-medium scattering Coalescence **brings up both** R_{AA} and v_2
  an effect that brings up toward experimental data, allows to disentagle the two

<u>Phase-space coalescence: quark recombination</u>

$$f_M(P_H = p_1 + p_2) \approx f_q(p_1) \otimes f_{\bar{q}}(p_2) \otimes \Phi_M(\Delta x, \Delta p)$$

<u>Independent Fragmentation</u>

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

→Add momenta: P_T^H from low p_T quark

→ Enhance elliptic flow v_2 by n_q scaling

$$n_q \, v_2(n_q p_T)$$

Hadronization play an important role in AA to determine R_{AA} and v_2 of D meson

→ Determintation of transp. coeff. $D_s(T)$

… but there has been a surprise both in AA but even in pp@TeV

In-medium modification of hadronization even in pp@TeV

Phase-space coalescence

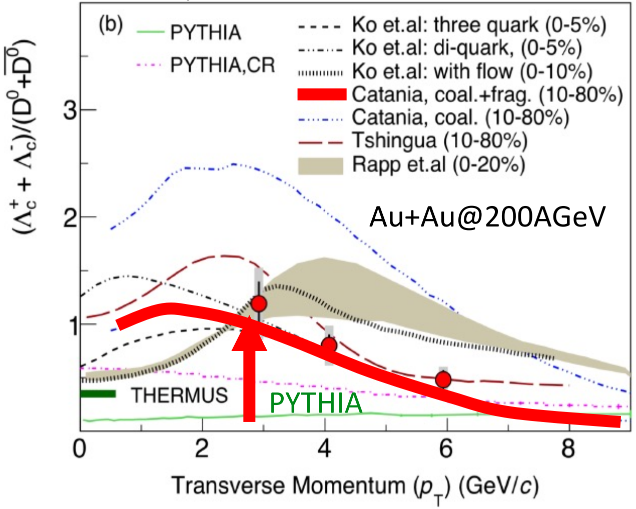
Parton Distrib. Funct. — Hadron Wigner function

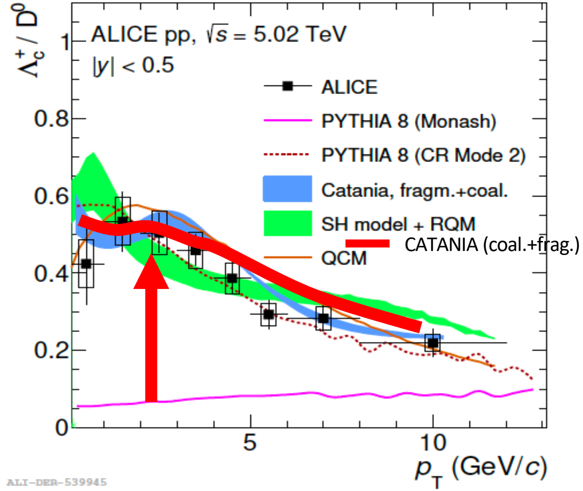
$$\frac{dN_{Hadron}}{d^2 p_T} = g_H \int \prod_{i=1}^{n} p_i \cdot d\sigma_i \frac{d^3 p_i}{(2\pi)^3} f_q(x_i, p_i)\, f_W(x_1, \ldots, x_n; p_1, \ldots, p_n)\, \delta(p_T - \Sigma_i\, p_{iT})$$

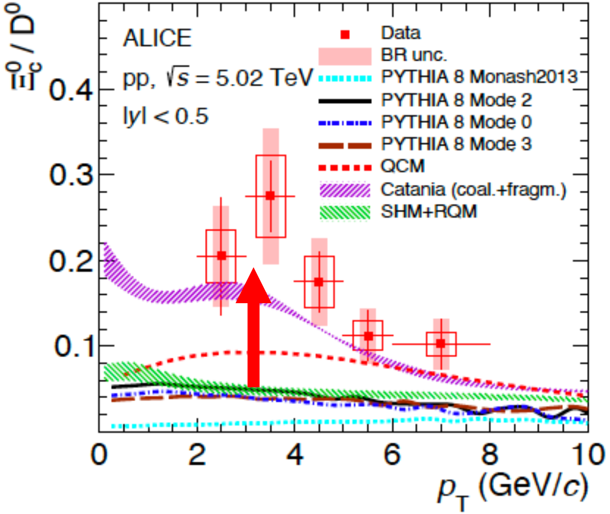
Fragmentation

$$\frac{dN_h}{d^2 p_h} = \Sigma_f \int dz \frac{dN_f}{d^2 p_f} D_{f \to h}(z)$$

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



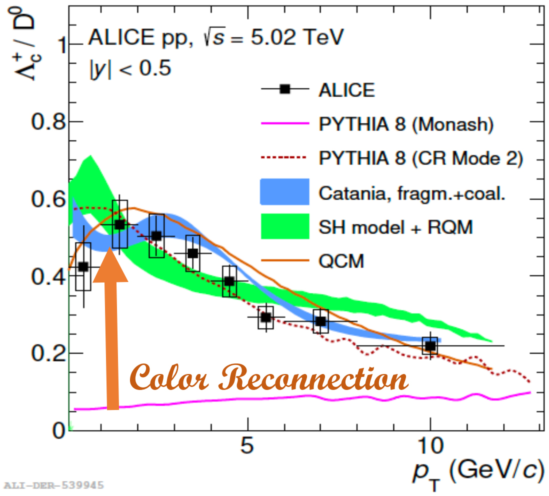


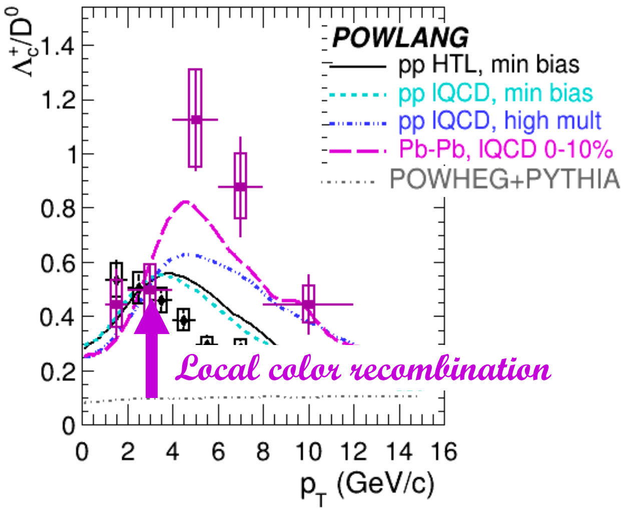


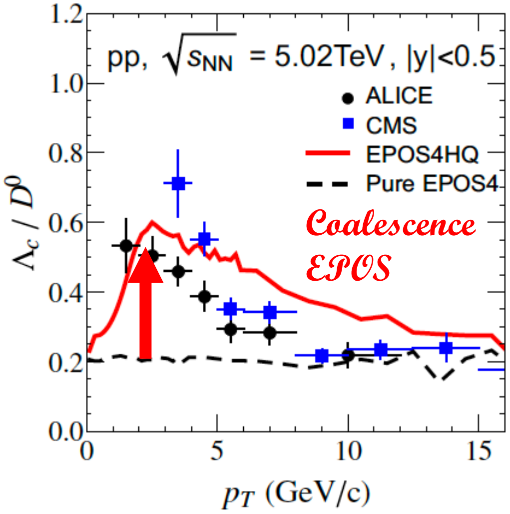
- Large Heavy Baryon to Meson production ~ a factor of 10 larger than in e+e- or PYTHIA
- Breaking of Universal Fragmentation Function already in pp in HF sector

HF hadronization has stimulated several developments

- **PYHTIA** beyond Leading Color (LC)→ Color Reconnection (CR) in pp
- Coalescence+Fragmentation approach applied also to pp
- Local Color Recombination: **POWLANG** in AA and in pp
- Inclusion of HF Coalescence+ Fragmentation in **EPOS** (pp &AA)

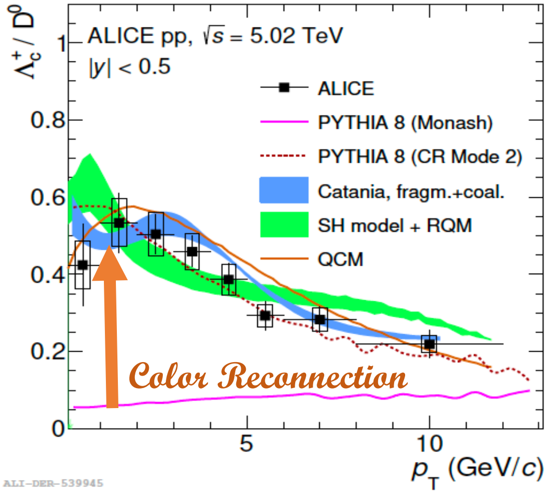


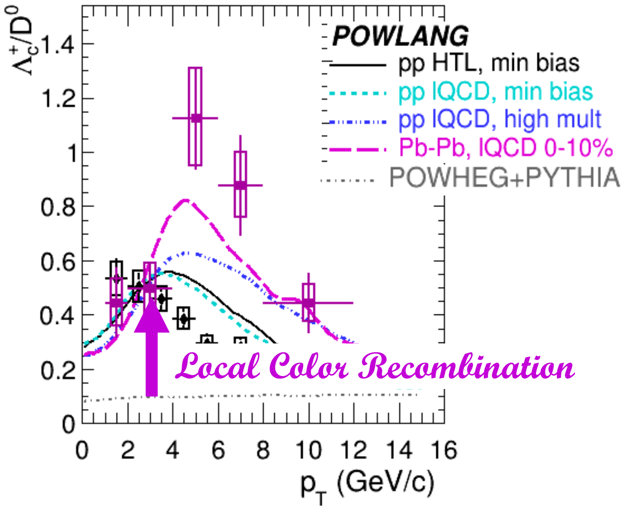




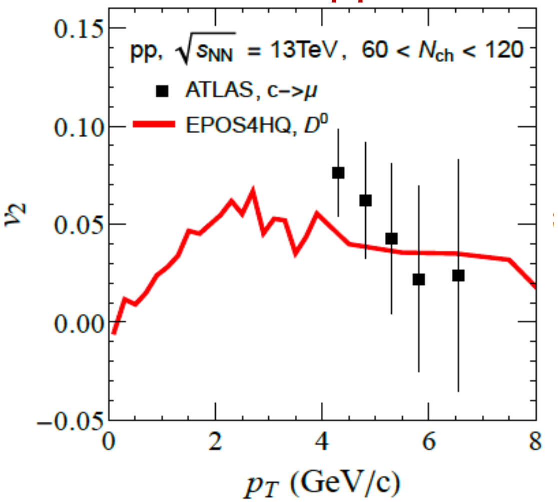
HF hadronization has stimulated several developments

- **PYHTIA** beyond Leading Color (LC)→ Color Reconnection (CR) in pp
- Coalescence+Fragmentation approach applied to pp
- Local Color Recombination: **POWLANG** in AA and in pp
- Inclusion of HF Coalescence+ Fragmentation in **EPOS** (pp &AA)





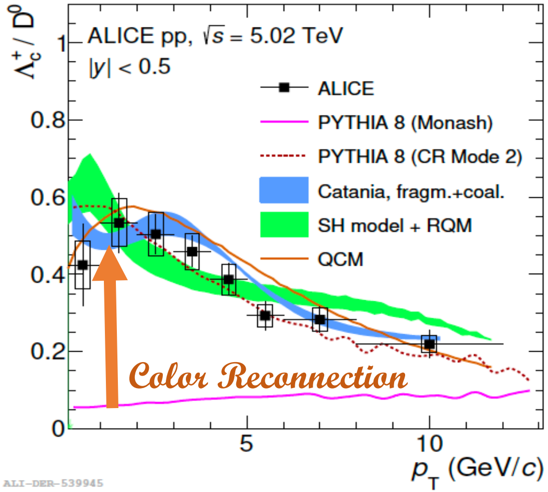
even in pp v_2

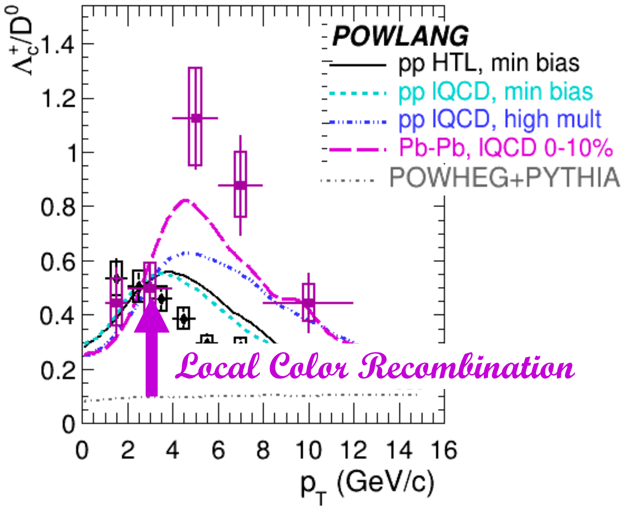


- Yields modified from e^+e^- (e^-p) to pp, then from pp to AA mostly coupling to flowing QGP medium modifies p_T shape of the ratio Λc/D?

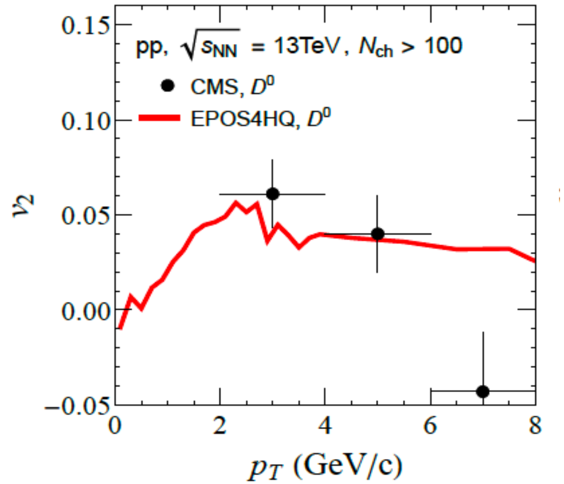
HF hadronization has stimulated several developments

- **PYHTIA** beyond Leading Color (LC)→ Color Reconnection (CR) in pp
- Coalescence+Fragmentation approach applied to pp
- Local Color Recombination: **POWLANG** in AA and in pp
- Inclusion of HF Coalescence+ Fragmentation in **EPOS** (pp &AA)





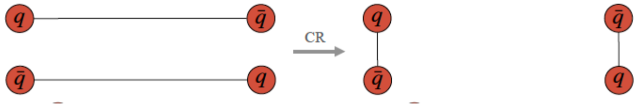
even in pp v_2



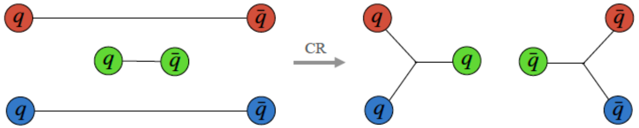
- Yields modified from e^+e^- (e^-p) to pp, then from pp to AA mostly coupling to flowing QGP medium modifies p_T shape of the ratio Λc/D?

PYTHIA Color Reconnection/ Local Color neutralization

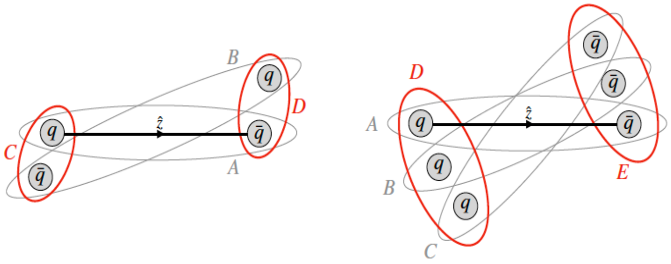
Altmann et al., arXiv 2405.19137



(a) Dipole-type reconnection.



Baryonic reconnection



(a) Mesonic reconnection. (b) Baryonic reconnection.

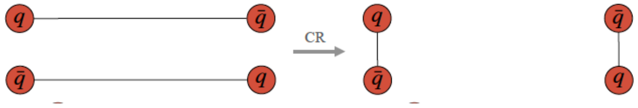
Leading Color ($N_c \to \infty$): Prob. of Local Color neutralization→0

- ❑ When string color reconnection is switched-on in pp
  - → Very large baryon Λ_c, Σ_c enhancement
  - → not so relevant for D, like coalescence+fragmentation

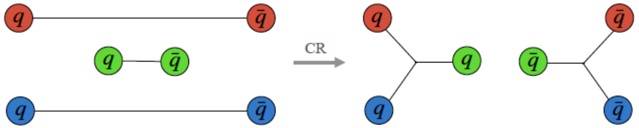
➢ Not indipendent strings - **Local reconnection → string energy minimization→ smaller invariant mass** close to D meson states

PYTHIA Color Reconnection/ Local Color neutralization

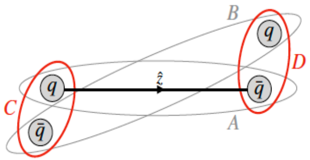
Altmann et al., arXiv 2405.19137



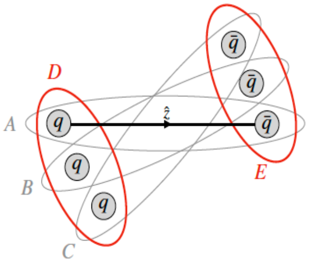
(a) Dipole-type reconnection.



Baryonic reconnection



(a) Mesonic reconnection.



(b) Baryonic reconnection.

Leading Color ($N_c \rightarrow \infty$): Prob. of Local Color neutralization→0

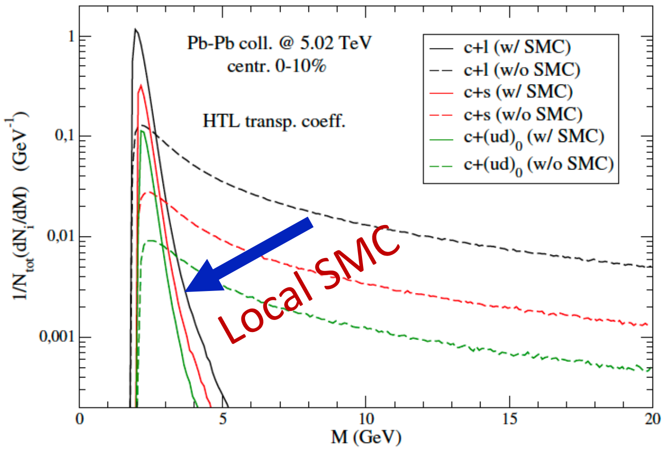
- When string color reconnection is switched-on in pp
  - → Very large baryon Λ_c, Σ_c enhancement
  - → not so relevant for D, like coalescence+fragmentation

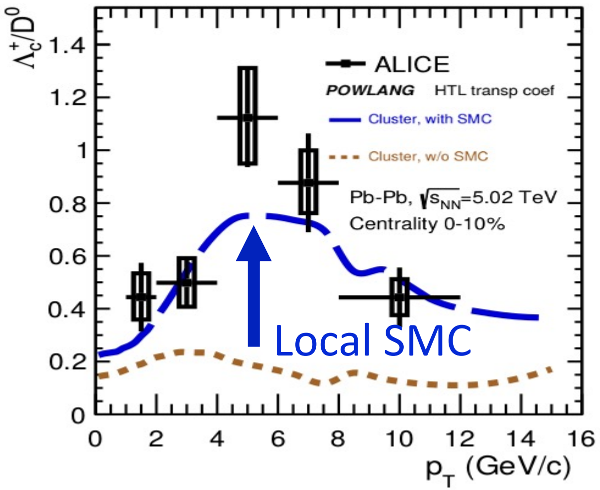
- Not indipendent strings - **Local reconnection → string energy minimization→ smaller invariant mass** close to D meson states

Needed switch-off of **diquark *l*=*1*** junction suppression *(set for e^+e^-). Removing it → Agreeement to data of $\Lambda_c \leftarrow \Sigma_c$*
It goes in the direction of simply recombine according to SU(3)

POWLANG Local Color Neutralization

A. Beraudo et al., EPJC82(2022) [AA]
A. Beraudo et al., PRD109(2024) [pp]





Charm recombine ***locally*** with quarks & diquarks assumed thermally distributed + radial flow:

$$n_l \cong g_s g_I \frac{T_H m_l^2}{2\pi^2} K_2\left(\frac{m_l}{T_H}\right) \qquad l = q, \bar{q}, s, \bar{q}, (ud)_0, (sq)_0, (sq)_1, \ldots$$

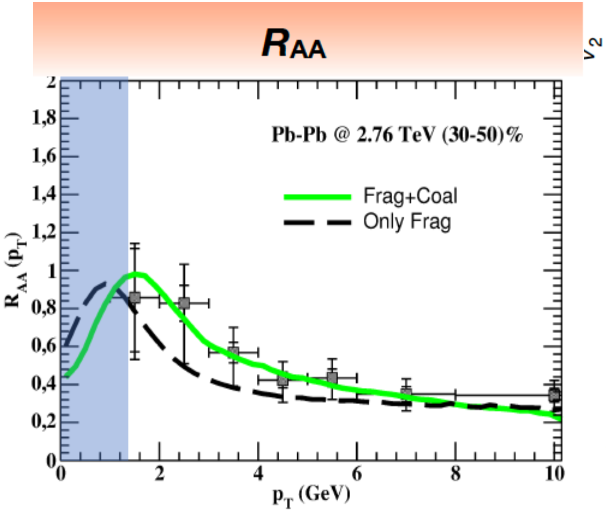
Dense medium (pp &AA) → **local** color statistical neutralization

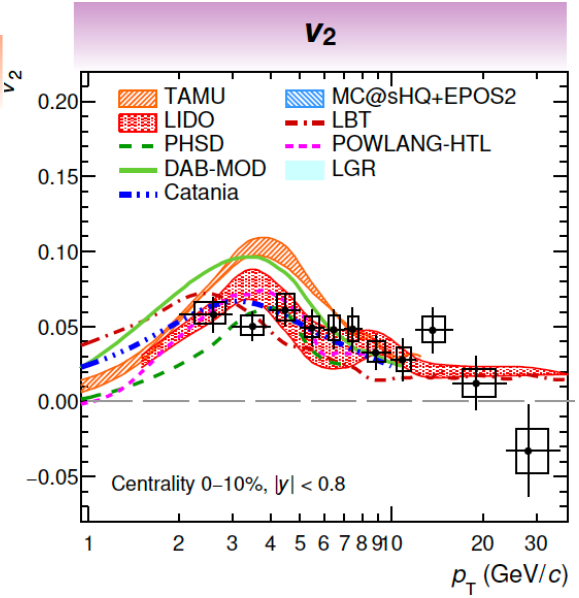
Narrow invariant M distribution close to D meson masses

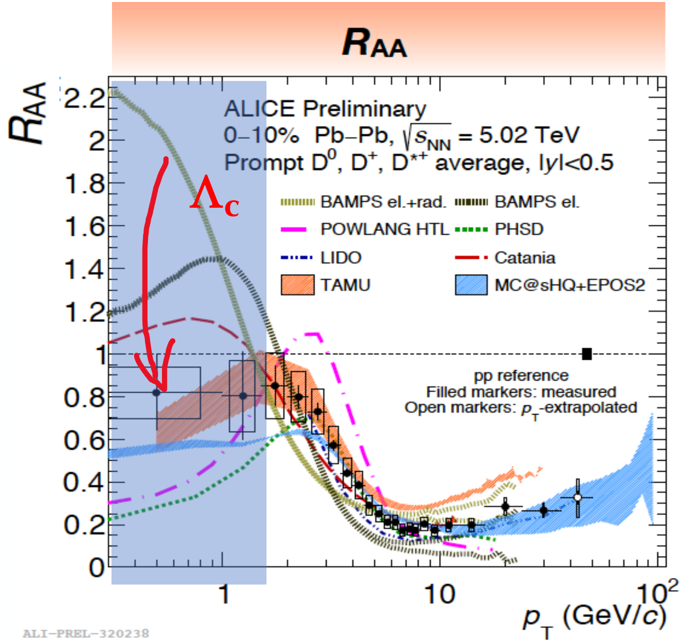
not large M string breaking with large y endpoints

→ Qualitatively similar to PYTHIA with local CR
Coalescence or Resonance Recombination
including strong impact on $v_2(p_T)$ from c→ D, Λ_c (all recomb.)

Studying the HF in uRHIC after Run2







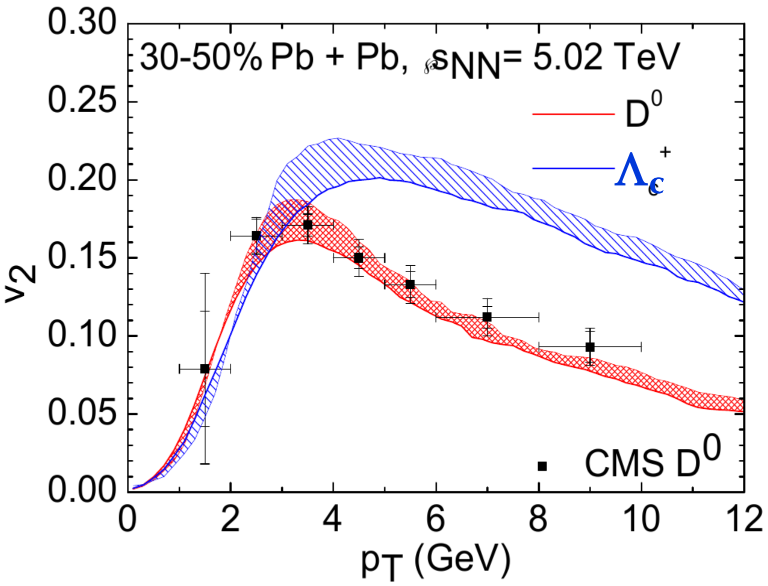
- ➢ Most models studies at p_T>1.5-2 GeV and mainly not including impact of hadroning into Λ_c
- ➢ To be done a new assesement of D_s(T) with upgraded approach:
  - → compare to LQCD & AdS/CFT **need data p_T→ 0**
  - → need precision data at low p_T not only for D, necessary Λ_c , important Ξ_c , Ω_c
  - → need not only R_{AA} and v_2 but also more esclusive observables → needed HL-LHC

"See" Hadronization mechanism through elliptic flow

If the enhancement of the yield comes from quark coalescence it should be associated to

→ Large v_2 of $\Lambda_c \sim n_q v_{2q}(n_q p_T)$, visible at intermediate p_T

Effect to be measured in AA; will it be seen also in pp? [for AA Run3-4]



He and Rapp, PRL 2020

✓ It should be also confirmed for Ξ_c [Run 5-6]

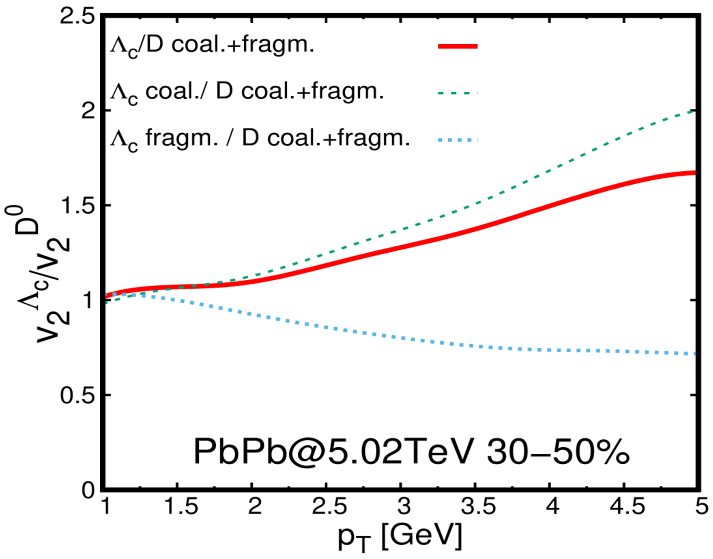
➢ Would PYHTIA-CR predict finite v_2 of D, Λ_c in pp? by String shoving? Can it predict D, Λ_c systematics?

"See" Hadronization mechanism through elliptic flow

If the enhancement of the yield comes from quark coalescence it should be associated to

→ Large v_2 of $\Lambda_c \sim n_q v_{2q}(n_q p_T)$, visible at intermediate p_T

Effect to be measured in AA; will it be seen also in pp? [for AA Run3-4]



Minissale, Plumari, VG, in preparation

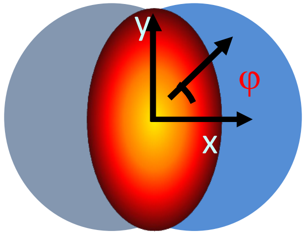
✓ It should be also confirmed for Ξ_c [Run 5-6]

➢ Would PYHTIA-CR predict finite v_2 of D, Λ_c in pp? by String shoving? Can it predict D, Λ_c systematics?

Methods/tools of AA allow better insight into Hadronization in pp.

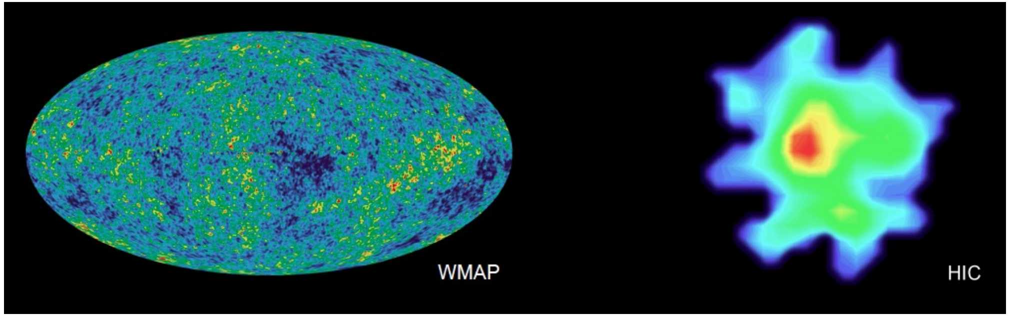
Able to «see» even the local Temperature. fluctuations of the QGP

Transverse view

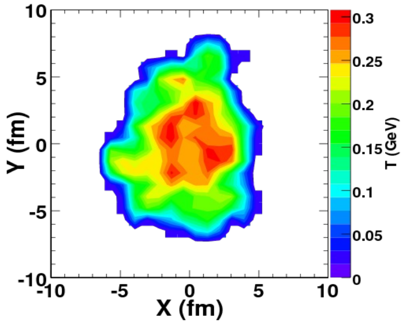


Relativistic HIC
in ’90s, ’00 till about 2005

Anisotropies only with
even parity due to symmetry
→ v_2 elliptic flow

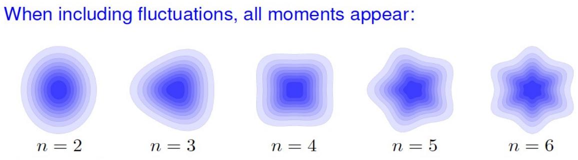


Transverse view of HIC,nowdays



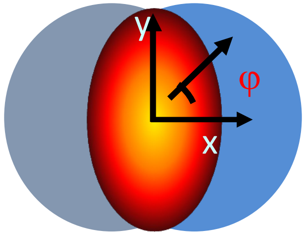
All harmonics appearing
with different weights.

$$v_n = \langle \cos(n\varphi) \rangle$$



Able to «see» even the local Temperature. fluctuations of the QGP

Transverse view



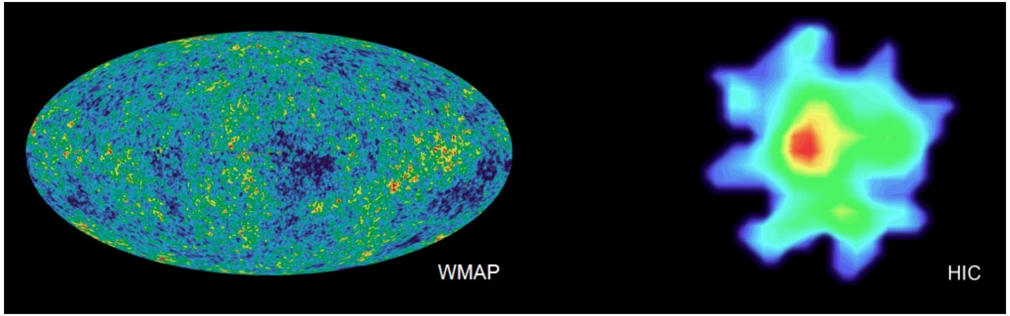
Relativistic HIC

in '90s, '00 till about 2005

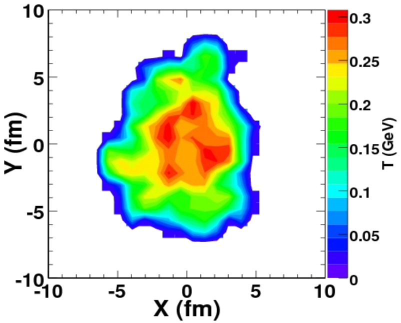
Anisotropies only with

even parity due to symmetry

→ v_2 elliptic flow



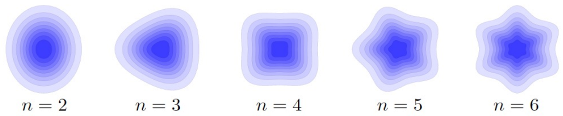
Transverse view of HIC,nowdays



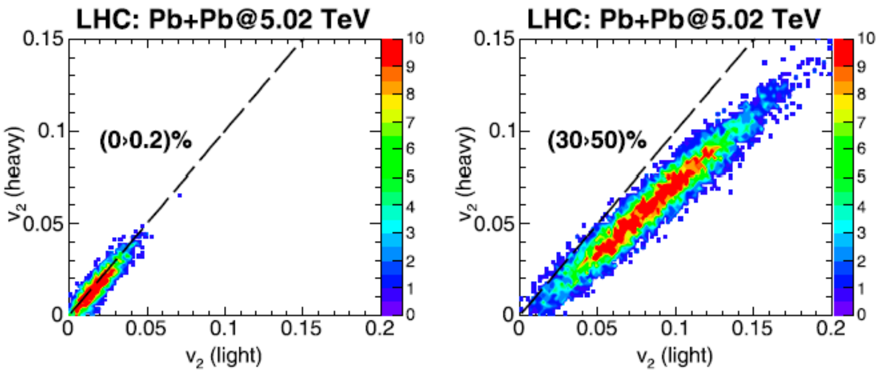
All harmonics appearing with different weights.

$$v_n = \langle \cos(n\varphi) \rangle$$

When including fluctuations, all moments appear:



A powerful not yet exploited for HQ especially at low p_T lack statistics

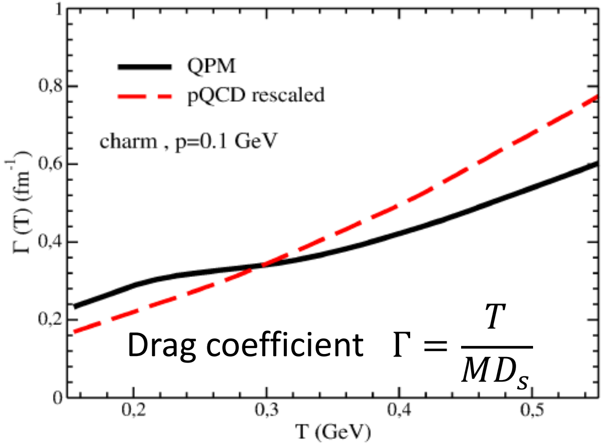


HL-LHC allows to access v_n light-HQ correlation

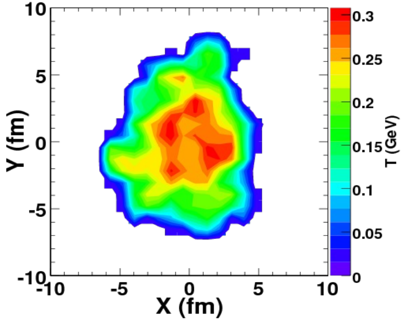
Event-by-event coupling of the anisotrpy of the bulk (light) and the charm (heavy) one

→ Much more precise determination of the strength interaction: drag $\Gamma \sim 1/D_s$

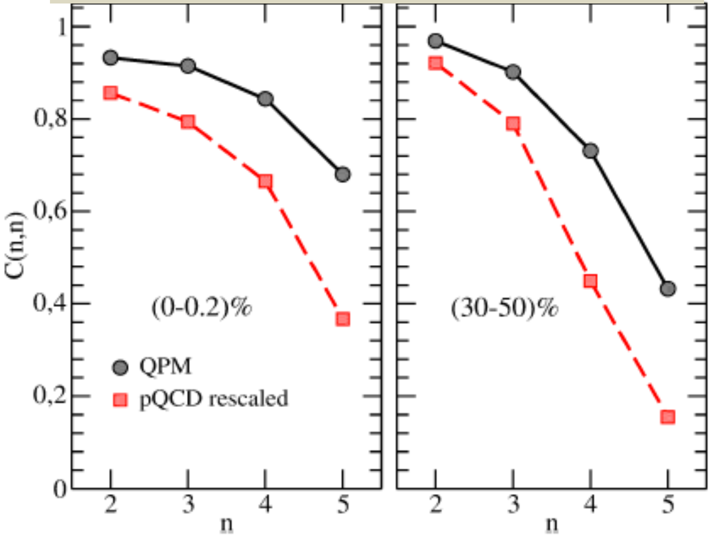
$$C(v_n^{light}, v_m^{heavy}) = \left\langle \frac{(v_n^{light} - \langle v_n^{light} \rangle)(v_m^{heavy} - \langle v_m^{heavy} \rangle)}{\sigma_{v_n^{light}} \sigma_{v_m^{heavy}}} \right\rangle$$



Drag coefficient $\Gamma = \frac{T}{MD_s}$



Very large sensitivity to T dep. of Ds



S. Plumari et al., Phys.Lett.B 805 (2020)

Could be accessible starting from Run 4 for v_2 may be, $v_{3,4}$ Run 5-6

A very solid and high precision comparison to LQCD, development of NRQCD-EFT, quantification of interaction only by D_s(full Brownian motion)

requires a full HQ , but M_c~ gT, <p> at T~ 300-500 MeV → full Heavy is Bottom

Relevance of direct Bottom measurements

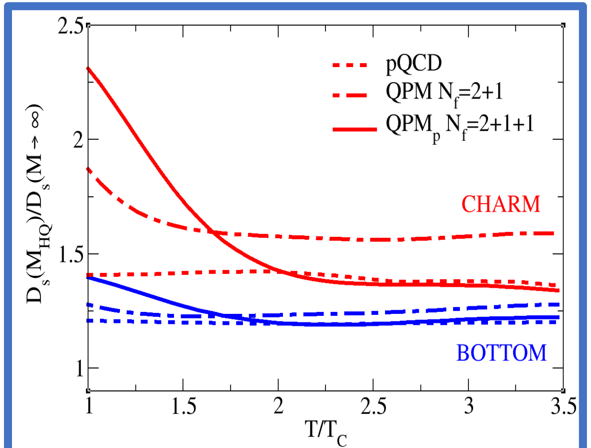
- Quite close to **M→ ∞** & **Non Relativistic** limit

  → more solid comparison to LQCD/NRQCD for $D_s(T)$

- $M_Q(T) >> T$, gT full **Brownian motion**, satisfy fluctuations dissipation theorem

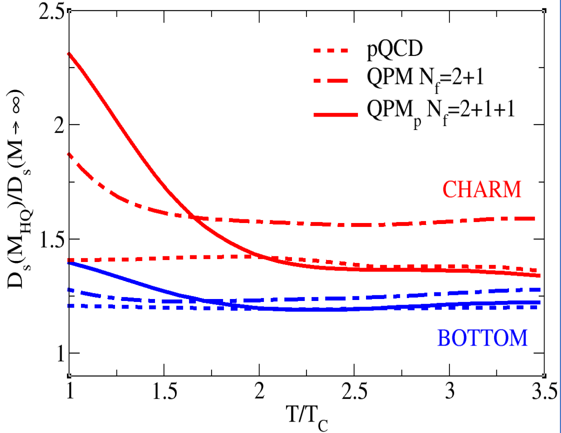
  → damps uncertainties in transport evolution (Langevin, Boltzmann, Kadanoff-Baym…)

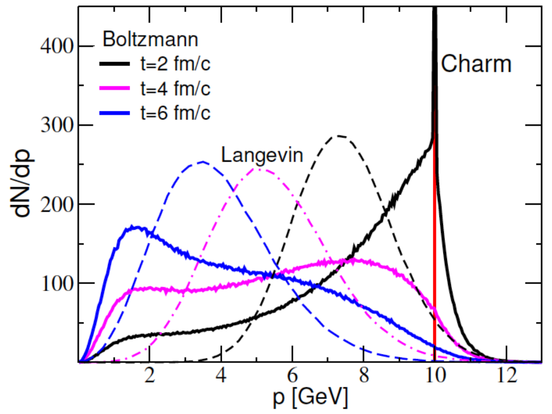
- Impact of **hadronization** on dN/dp_T & $v_n(p_T)$ moderate and less different by fragmention



Relevance of direct Bottom measurements

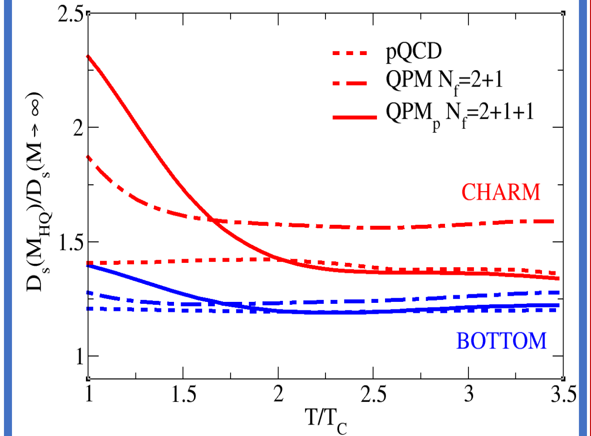
- Quite close to **M→ ∞** & **Non Relativistic** limit
  → more solid comparison to LQCD/NRQCD for $D_s(T)$
- $M_Q(T) >> T$, gT full **Brownian motion**, satisfy fluctuations dissipation theorem
  → damps uncertainties in transport evolution (Langevin, Boltzmann, Kadanoff-Baym…)
- Impact of **hadronization** on dN/dp_T & $v_n(p_T)$ moderate and less different by fragmention

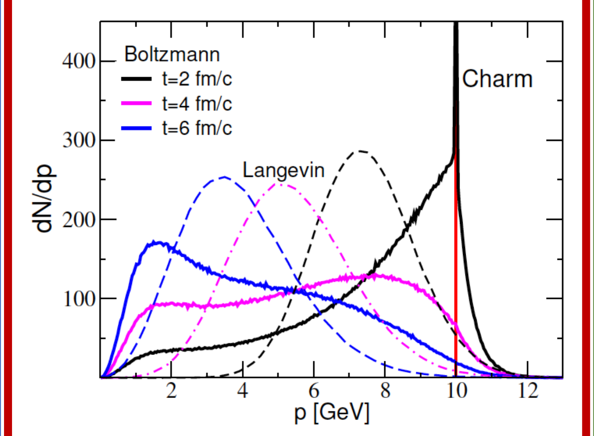


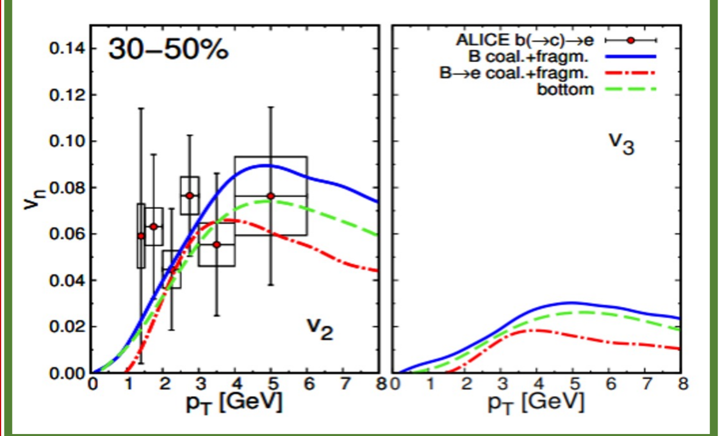


Relevance of direct Bottom measurements

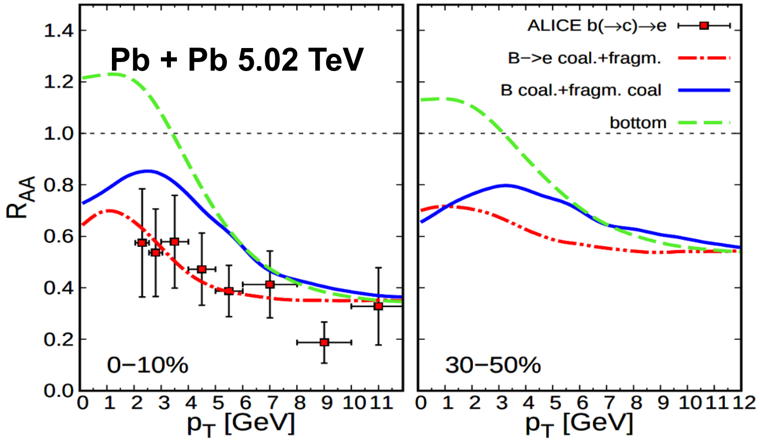
- Quite close to **M→ ∞** & **Non Relativistic** limit
  → more solid comparison to LQCD/NRQCD for $D_s(T)$
- $M_Q(T)$ >> T, gT full **Brownian motion**, satisfy fluctuations dissipation theorem
  → damps uncertainties in transport evolution (Langevin, Boltzmann, Kadanoff-Baym…)
- Impact of **hadronization** on dN/dp_T & $v_n(p_T)$ moderate and less different by fragmention
- Larger $\tau_{th}^{b} \sim M/T\ \tau_{th}^{c}$ more sensitive to dynamical evolution: carry more info

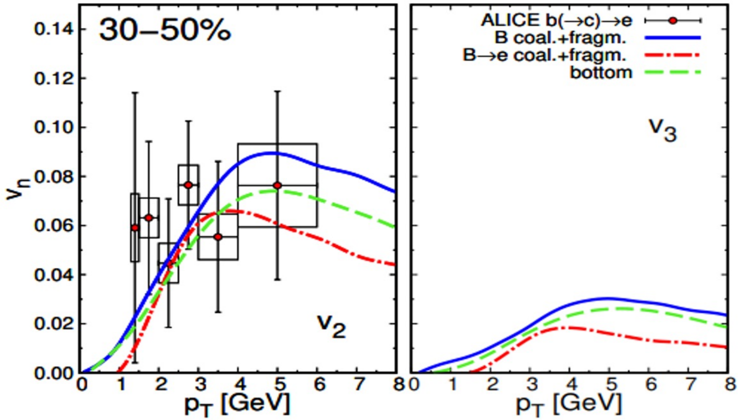






Extension of QPM to bottom dynamics: R_{AA} v_2, v_3





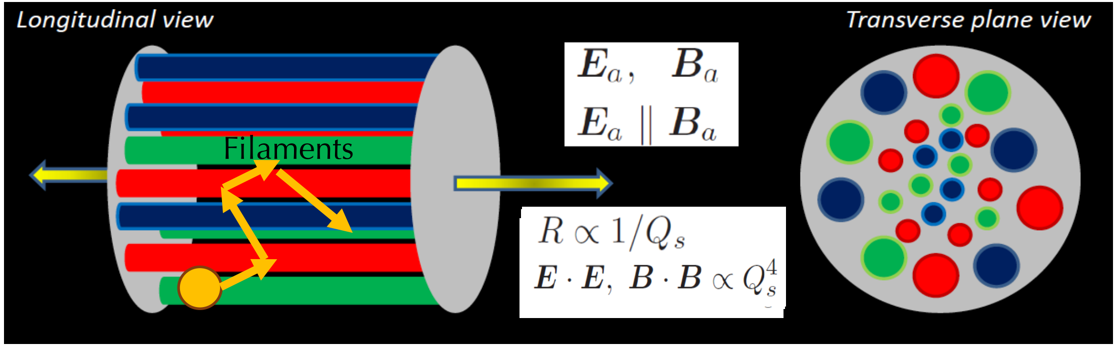
- No parameters changed wrt charm (only M_b), but :
  - agreement within still large uncertainty
  - no direct B data (semileptonic decay)
  - lack v_3
  - v_n(hard)-v_n(soft) correlation

→ Need for luminosity of Run 5-6

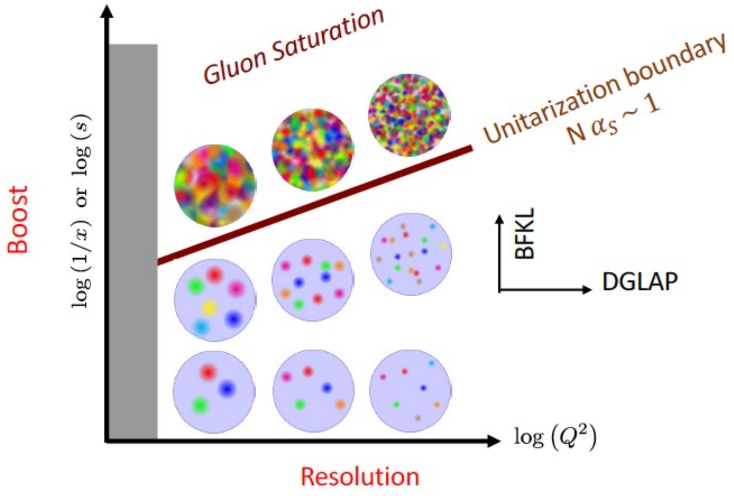
M.L. Sambataro et al., *PLB* 849(2024)

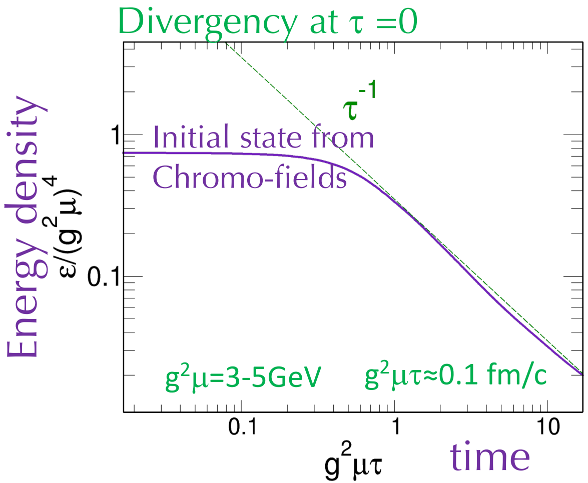
HQ probe of CGC/Glasma phase $0^+<t<0.3$ fm/c

Color Glass Condensate (CGC) is the high-energy limit of QCD in the BFKL direction in the plane [Q^2,x]?



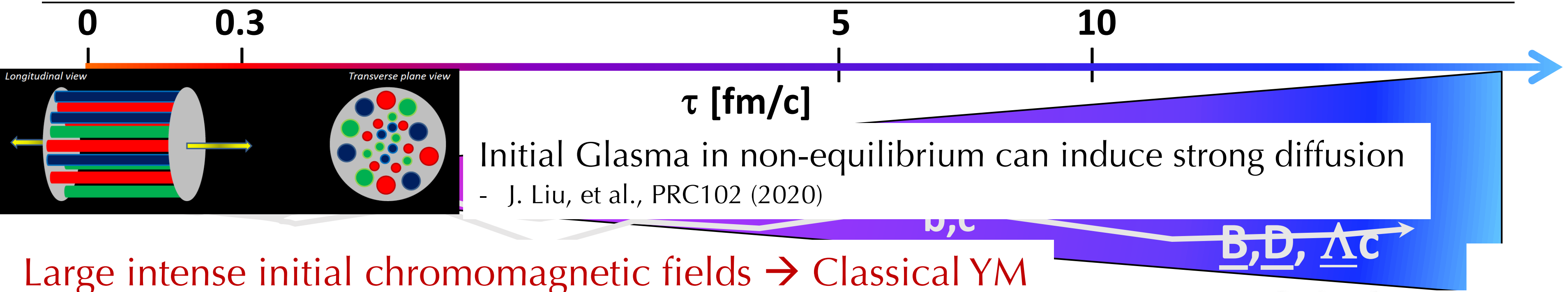
$Q_s \sim A^{4/3}$





- Solving the t=0 divergency $\varepsilon \sim \frac{1}{\tau}$ (≈ initio of the Collision Universe)
- The unknown very early stage would not destroy our current picture, but we look for signatures to spot from this phase [~ Early Universe, inflation]

Impact of Glasma phase

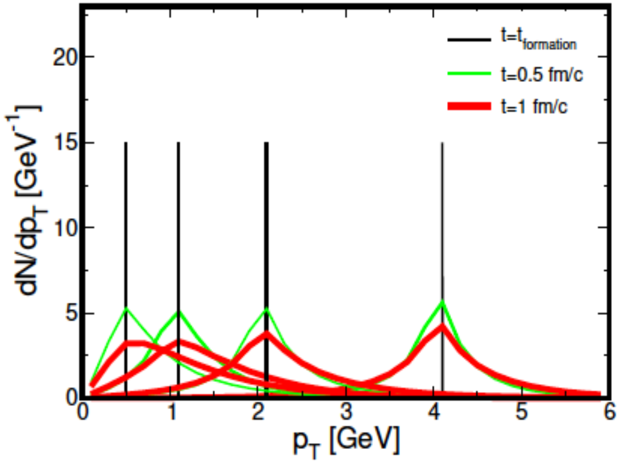


Initial Glasma in non-equilibrium can induce strong diffusion

- J. Liu, et al., PRC102 (2020)

Large intense initial chromomagnetic fields → Classical YM

Static box- SU(2)

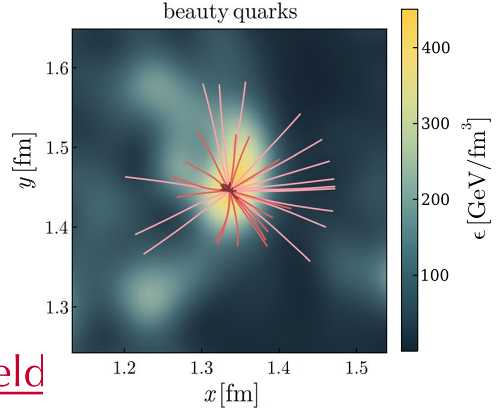


Solving classical Yang-Mills

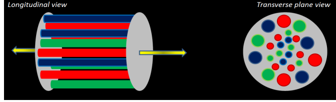
$$\frac{dA_i^a(x)}{dt} = E_i^a(x),$$
$$\frac{dE_i^a(x)}{dt} = \sum_j \partial_j F_{ji}^a(x) + \sum_{b,c,j} f^{abc} A_j^b(x) F_{ji}^c(x),$$

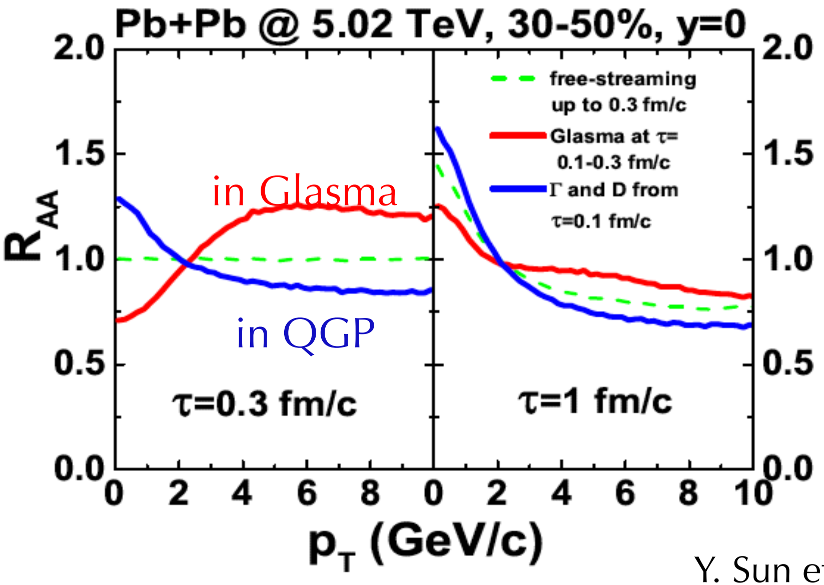
Heavy quark in the chromo magnetic field

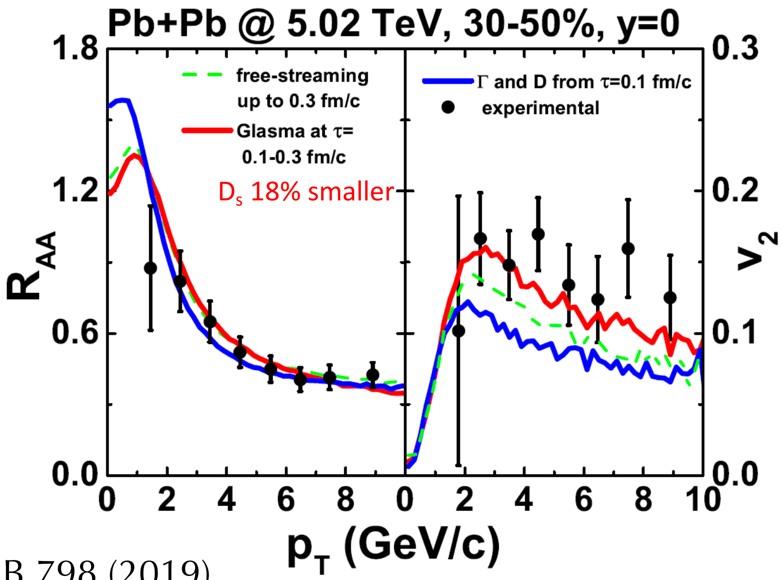
$$\frac{dx_i}{dt} = \frac{p_i}{E},$$
$$E\frac{dp_i}{dt} = Q_a F_{i\nu}^a p^\nu,$$
$$E\frac{dQ_a}{dt} = -Q_c \varepsilon^{cba} A_b \cdot p,$$



Potential impact on AA observables (starting at $\tau=\tau_{form}$- SU(2))





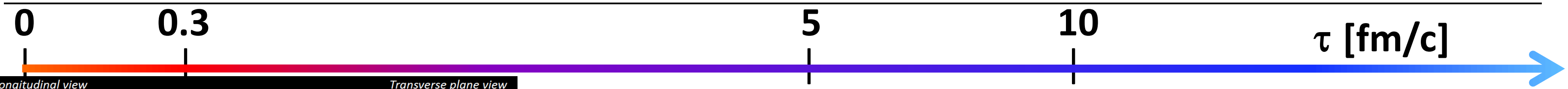


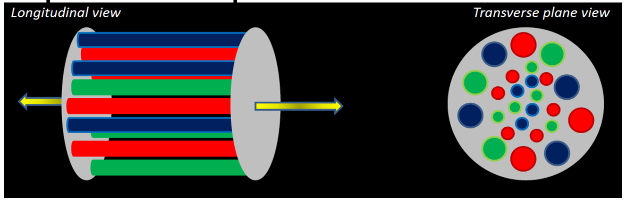
Y. Sun et al.,PLB 798 (2019)

- **Opposite to HQ in QGP**: Dominance of diffusion-like → initial **enhancement of $R_{AA}(p_T)$!!!**
- **Gain in v_2**: larger interaction in QGP stage needed to have same $R_{AA}(p_T)$ [18% smaller D_s]

High precison needed Run4, and likely alone not conclusive

Impact of Glasma phase



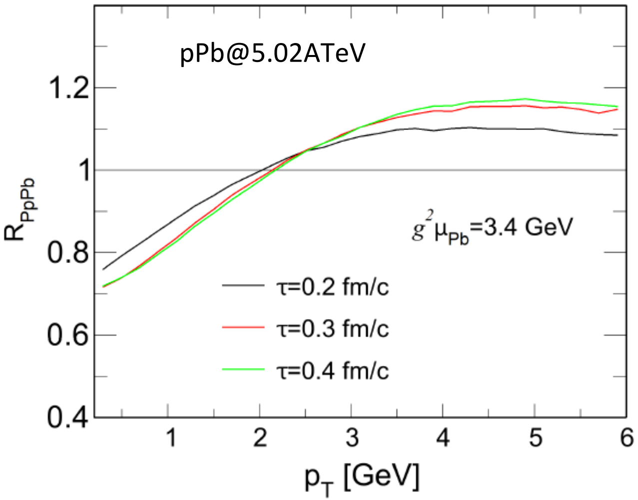


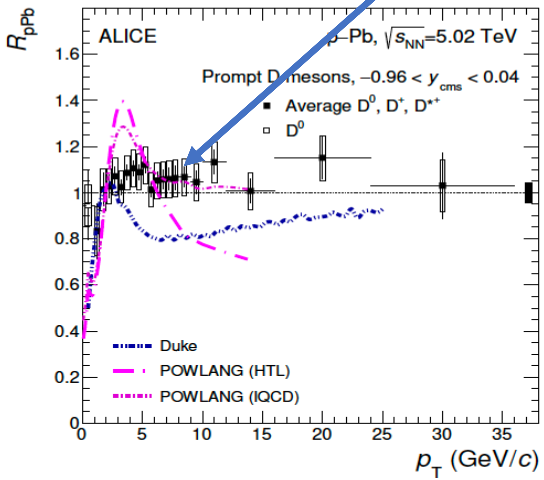
Initial Glasma in non-equilibrium can induce strong diffusion

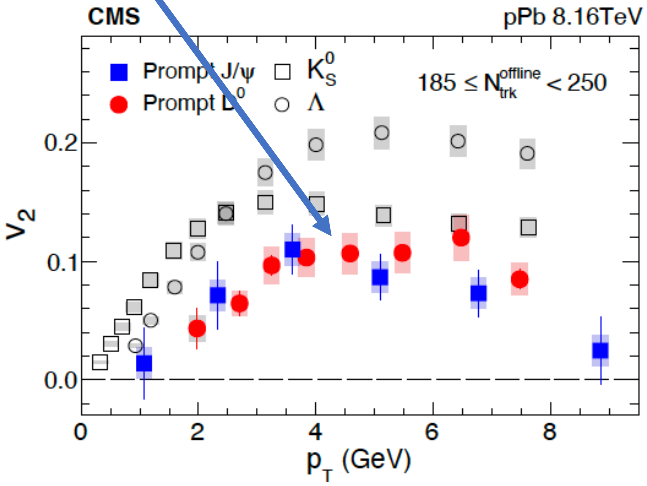
[J. Liu et al., PRC102 (2020)]

In pA collision it could solve the "puzzle":
$R_{pA} \sim 1$ and large v_2 of D meson

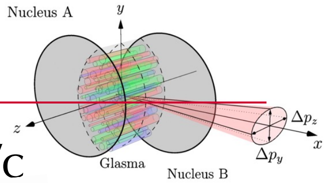
Phenomenological impact





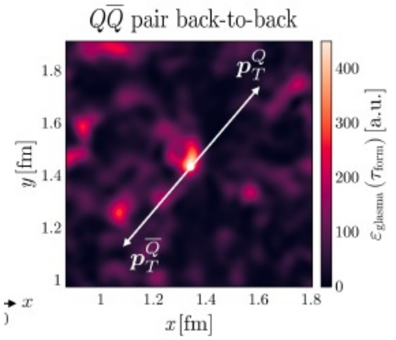


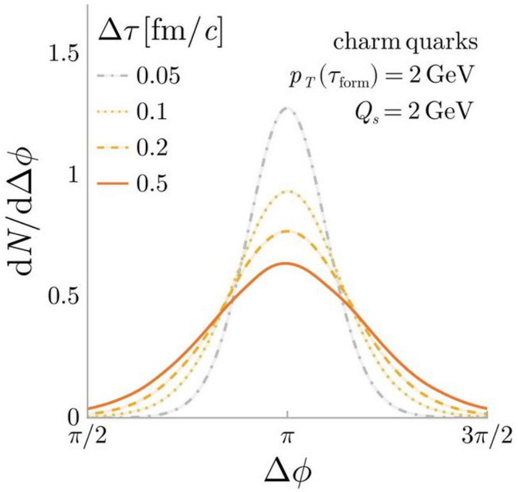
Glasma impact on angular $Q\bar{Q}$



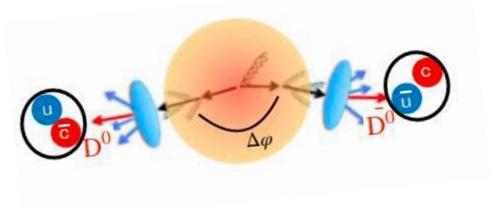
First study of azimuthal $Q\bar{Q}$ correlation: large decorellation in only 0.2 fm/c

Significant effect of glasma on HQ!





Nearly identical for bottom despite mass smaller t_{form}



pA collision should keep memory of it especially correlating it to R_{AA}, v_n:

- Identify Glasma phase
- quantify in medium E_{loss} $D_s(T)$
- solve the puzzle od R_{pA} ~1 and v_2 large

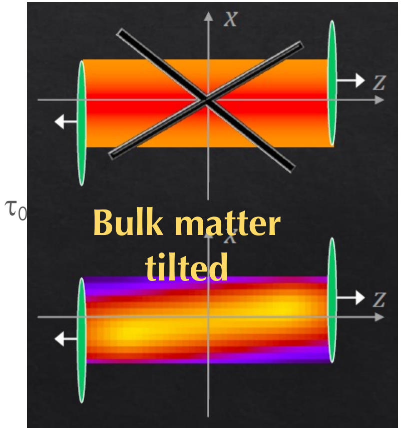
Calculation in SU(3) +longitudinal expansion

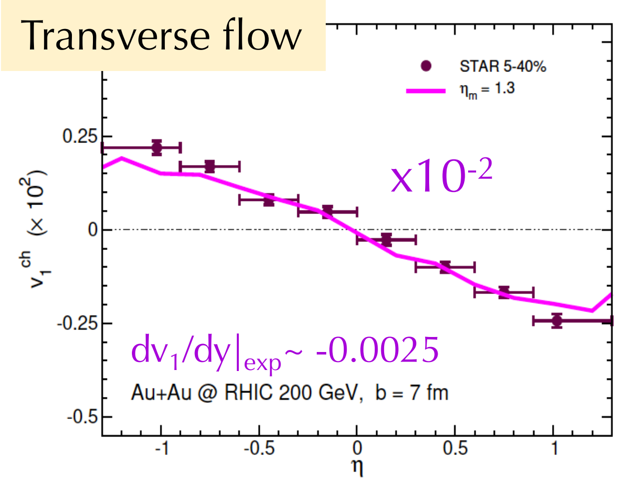
Accessible with high precsion for D and Λ_c from Run 5-6

D. Avramescu et al., arXiv:2409.10.565. [hep-ph]

HQ Surprise also transverse flow

L. Oliva et al., JHEP 05 (2021)





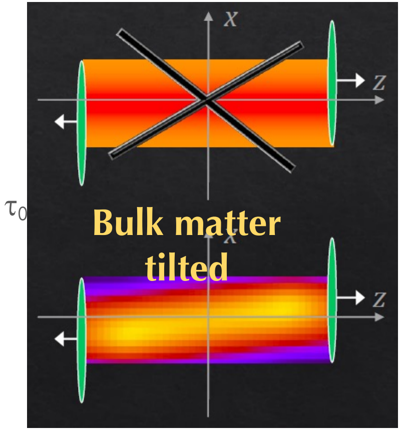
Would you expect charm quark to have a smaller v_2 ? Or a smaller one due to its mass?

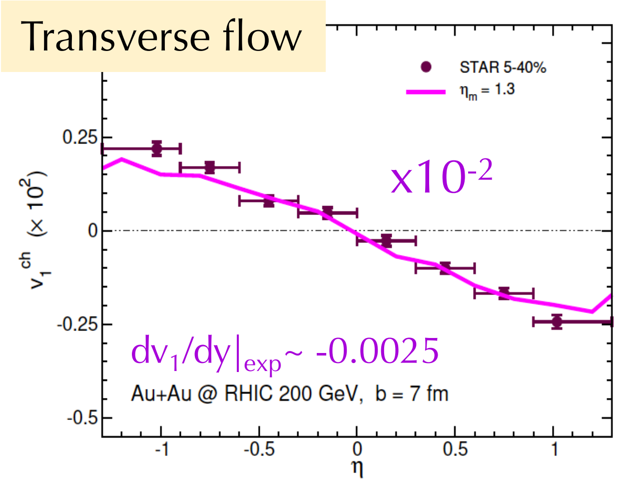
Very surprising!

v_1 (HQ) ~ 30 times v_1 light hadrons (π,K,..)

HQ Surprise also transverse flow

L. Oliva et al., JHEP 05 (2021)

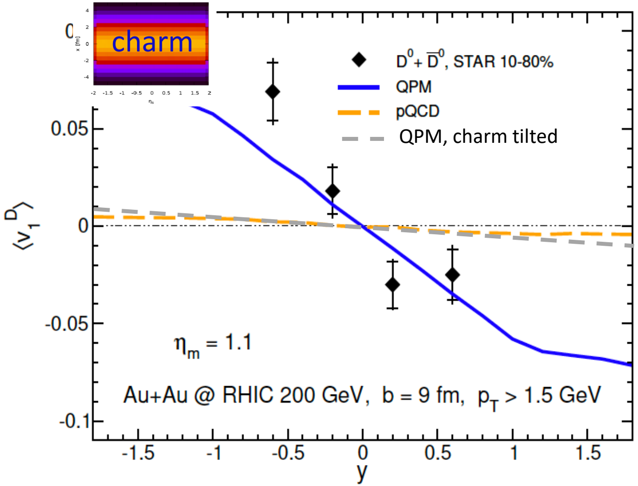


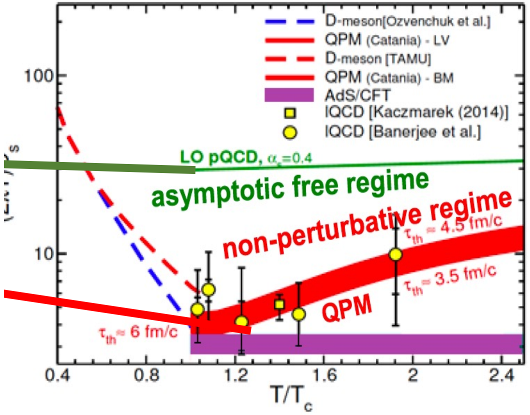


Would you expect charm quark to have a smaller v_2 ? Or a smaller one due to its mass?

Very surprising!

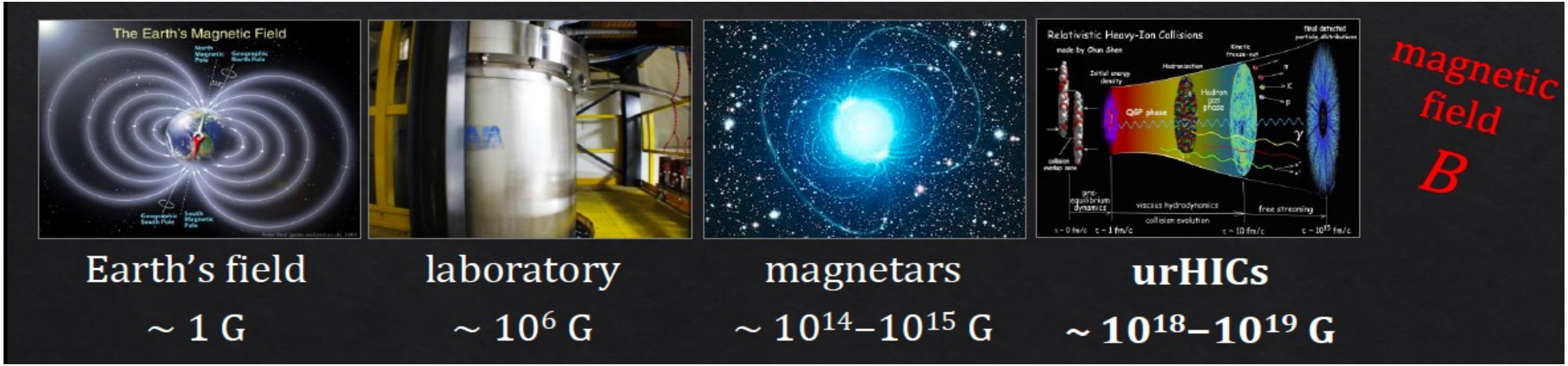
v_1 (HQ) ~ 30 times v_1 light hadrons (π,K,..)

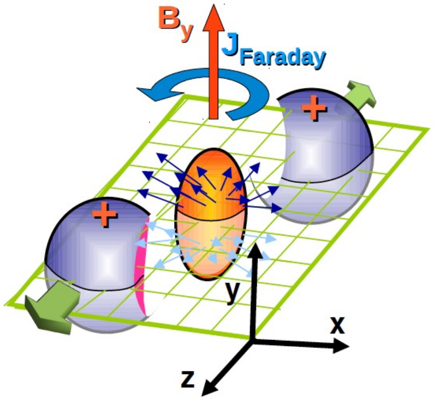


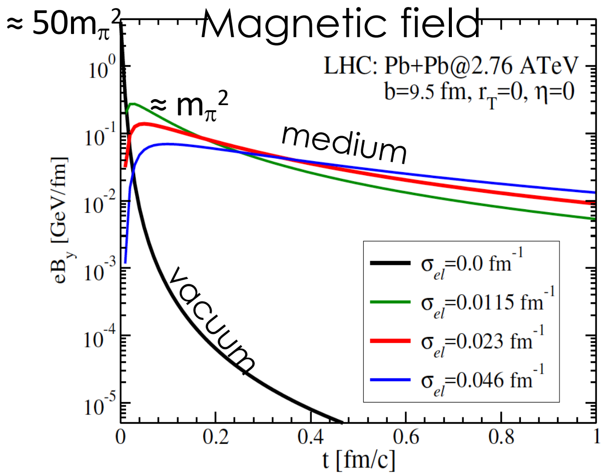


- **Needed non-perturbative HQ interaction close to AdS/CFT**
- Needed also initial "tilt" of bulk & no of HQ:
  - able to "see" 3D geometry with a resolution of ~ 0.5 fm

Charm as a probe of huge B Magnetic field







Schematic calculation: early time behavior quite uncertain theoretically (*non eq., back-reaction, glasma…*)

Impact of Magnetic Field on Charm

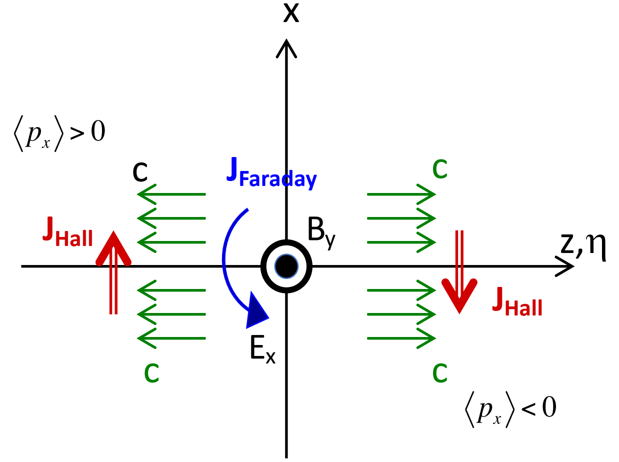
S.K.Das et al., PLB768(2017)

$$F_{ext} = qE + \frac{q}{E_p}(p \times B)$$

$\nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t}$

Faraday [+ Coulomb spectators]

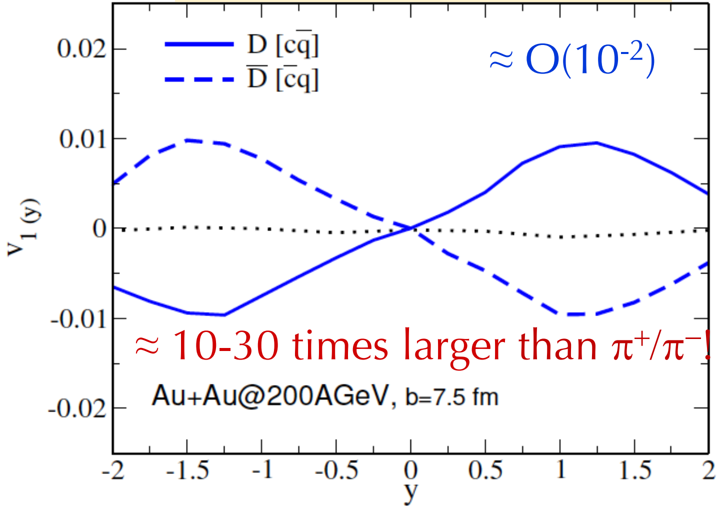
Lorentz



HQ best probe for v_1 from e.m. field:

- $t_{form} \approx 0.08$ fm/c when By is ≈ its maximum
- No contribution from neutral gluons diff. from π^+/π^-,p/$\bar{p}$
- $\tau_{th}(c) \approx \tau_{QGP} >> \tau_{e.m}$ (keep more memory effects)

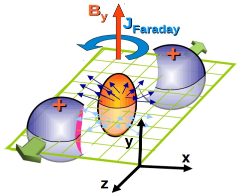
$\overline{D}^0 - D^0$ splitting in v_2

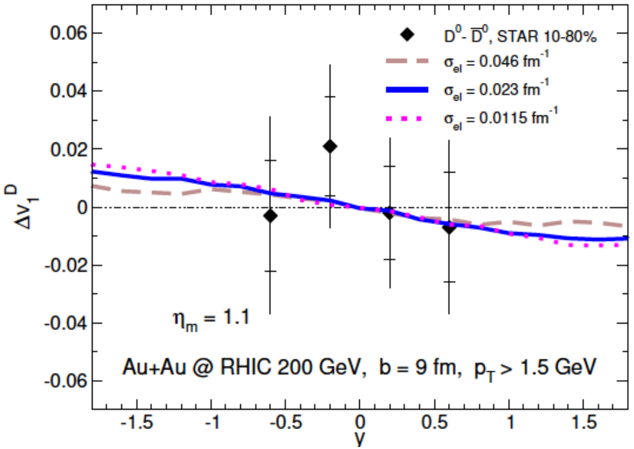


✧ Time decreasing magnetic B_y creates E_X that induces a current in opposite direction: delicate balance! [Cancellation at 95% level]

v_1 transverse flow current measurement

Oliva, Plumari, V.G., JHEP(2020)





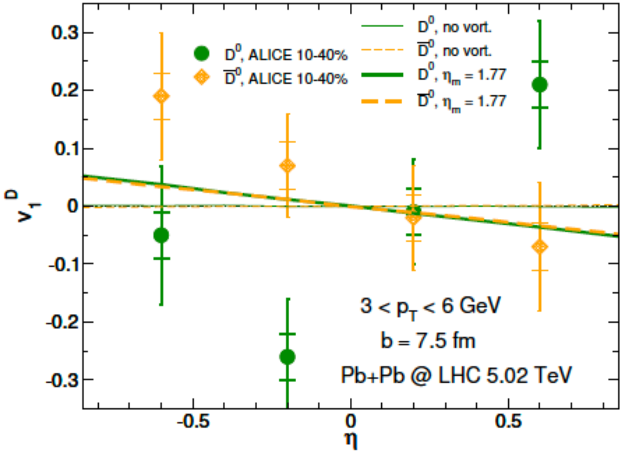
STAR@RHIC: $d(\Delta v_1)/dy|_{exp} = -0.011 \pm 0.024(stat) \pm 0.016(syst)$

≈ 10 times larger than charged, similar to S. Das et al., PLB768 (2017)

but with current precision **also consistent with 0!**

First measurement ALICE@LHC- large systematic/statistic error

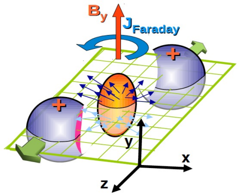
opposite sign & magnitude ≈ 40 times larger than predictions

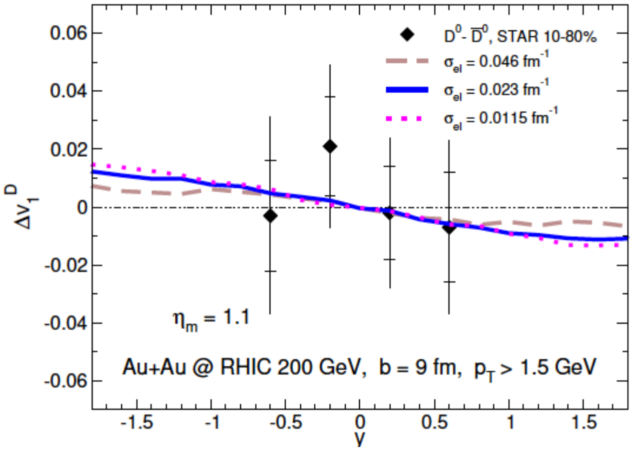


Need for high precision. Likely Run 4 or 5

v_1 transverse flow current measurement

Oliva, Plumari, V.G., JHEP(2020)





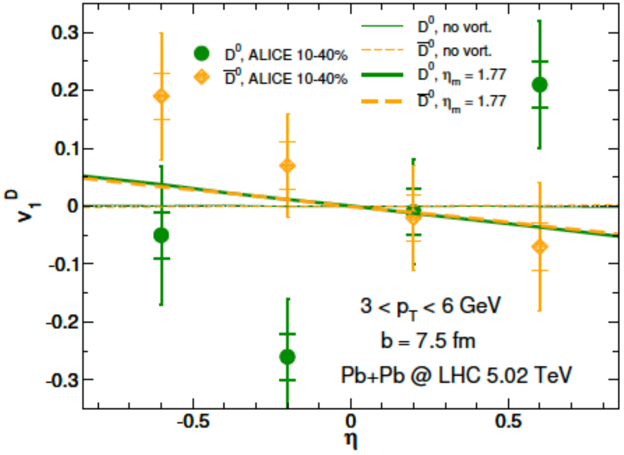
STAR@RHIC: $d(\Delta v_1)/dy|_{exp} = -0.011 \pm 0.024(stat) \pm 0.016(syst)$

≈ 10 times larger than charged, similar to S. Das et al., PLB768 (2017)

but with current precision **also consistent with 0!**

First measurement ALICE@LHC- large systematic/statistic error

opposite sign & magnitude ≈ 40 times larger than predictions

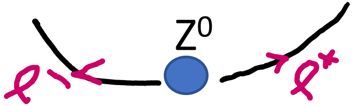


Need for high precision. Likely Run 4 or 5

- if $\Delta v_1(D^0 - \bar{D}^0)$ has an e.m. origin
  → **probe of deconfinement vs flavor**
- constraint on e.m. field → quantitative studies of **Chiral Magnetic Effect** (by **local CP violation** at high T)
  + several other effects

Magnetic field modifies Z^0 $l^\pm$ invariant mass and width in AA

Y.Sun, V. Greco, X.N. Wang, PLB827 (2022)



$\tau_{decay}(Z^0) = \tau_{form}(\text{charm}) = 0.08$ fm/c

→ Probe same magnetic field!

Acquire **Δp** by e.m field
-> modify invariant mass

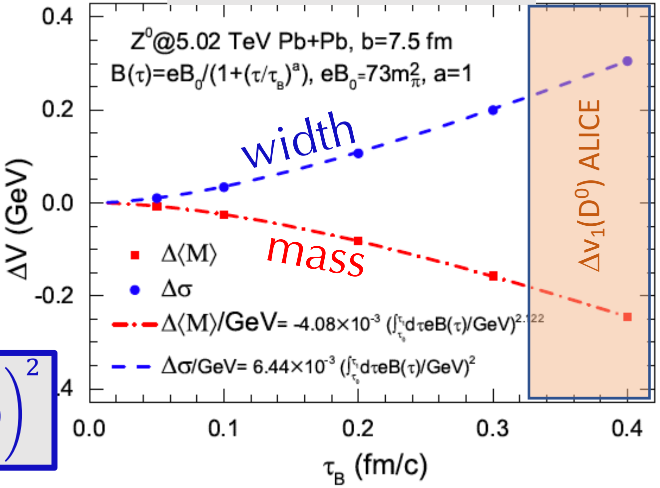
$$\rho(M) = \frac{1}{\pi}\frac{\Gamma/2}{(M-M_0)^2+\Gamma^2/4},$$

$$\Delta\langle M\rangle = k\left(\int_{\tau_0}^{\tau_1} d\tau\, e\, B(\tau)\right)^n$$

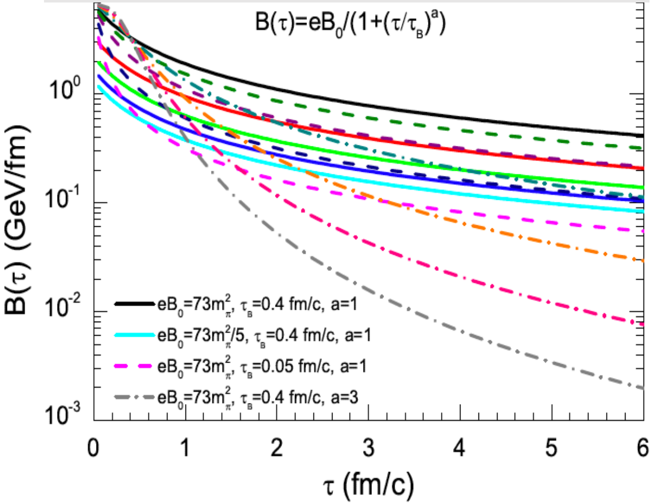
$n=2.16\pm0.16$, $k=-[3.9\pm1.2]\cdot 10^{-3}$

$$\Delta\sigma_{Z^0} = 6.4\cdot 10{-}3\left(\int_{\tau_0}^{\tau_1} d\tau\, e\, B(\tau)\right)^2$$

Changing lifetime τ_B



Wide range of B(τ) different pattern



Not accessible till now, may be Run 3-4 (CMS)

$\Delta v_1(\ell^+,\ell^-)$ would be even a more direct probe of B field peak expected at $p_T\sim 50$ GeV [Y. Sun, PLB 816(2021)] → Run 5-6?

Multicharm production + PbPb → OO

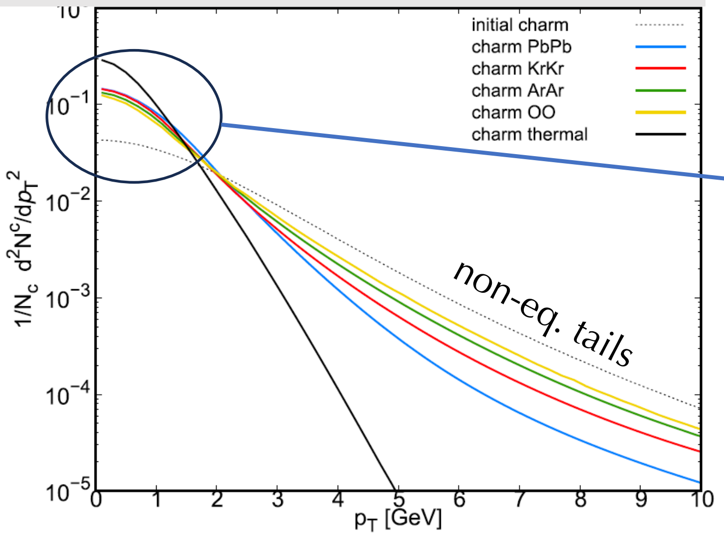
$\Xi_{cc}^{+,++}$, Ω_{scc}, Ω_{ccc}

Baryon		
$\Xi_{cc}^{+,++} = dcc, ucc$	3621	$\frac{1}{2}\,(\frac{1}{2})$
$\Omega_{scc}^{+} = scc$	3679	$0\,(\frac{1}{2})$
$\Omega_{ccc}^{++} = ccc$	4761	$0\,(\frac{3}{2})$

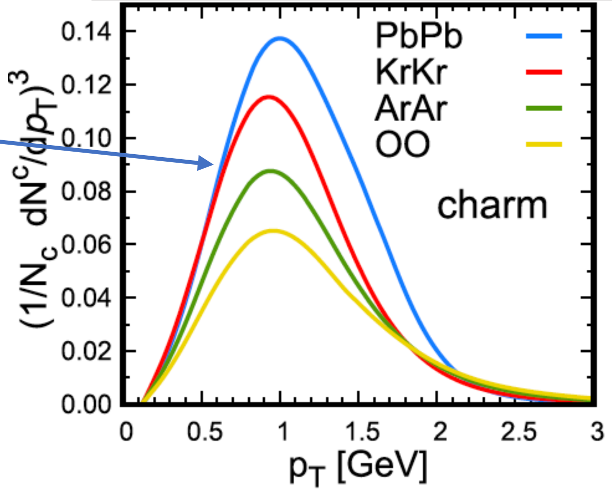
- ➢ Understand HQ in medium hadronization:
  [pure recombination , no fragmentation at low p_T at least]
- ➢ Ω_{ccc} very sensitive (to cubic power) to $(dN_{charm}/dp_T)^3$

A system size scanning is like looking to see ΔE versus L → dE/dx

Evolution of p_T charm vs system size

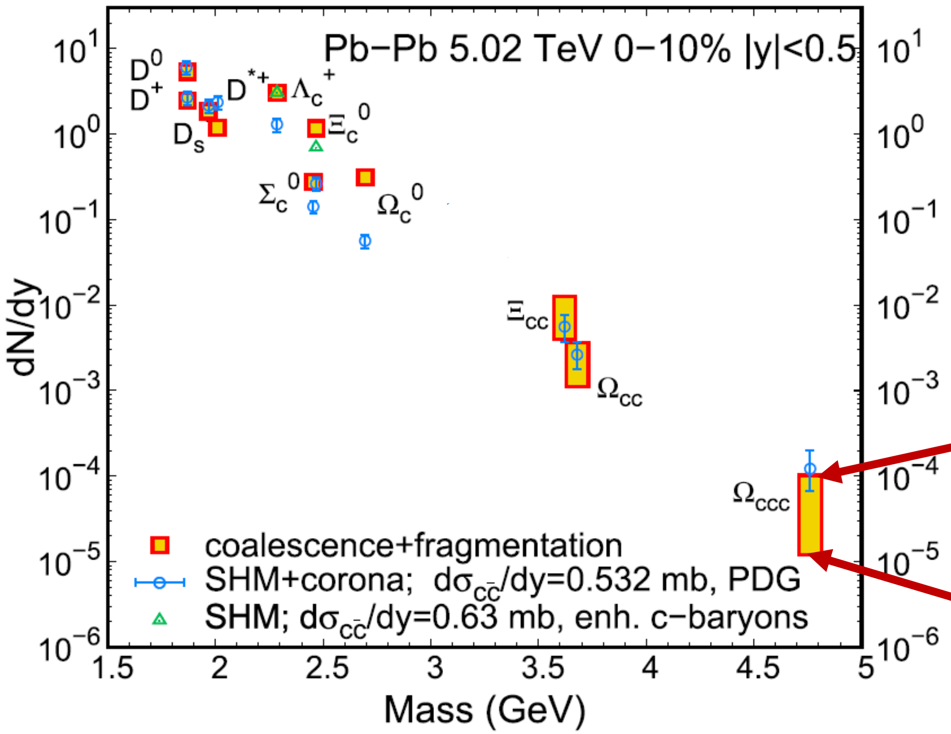


cubic of renormalized charm p_T distrib.



Yields in PbPb from coalescence vs SHM

V. Minissale, et al., EPJC 84(2024)



- Both Statistical model (SHM) & a naïve coalescence should lead to a scaling with

$$V\left(\frac{N_c}{V}\right)^c = N_c\left(\frac{N_c}{V}\right)^{c-1}$$ c= #of charm in Hadron

- Ω_{ccc} yield depends on $\left(\frac{dN_c}{dp_T}\right)^3$

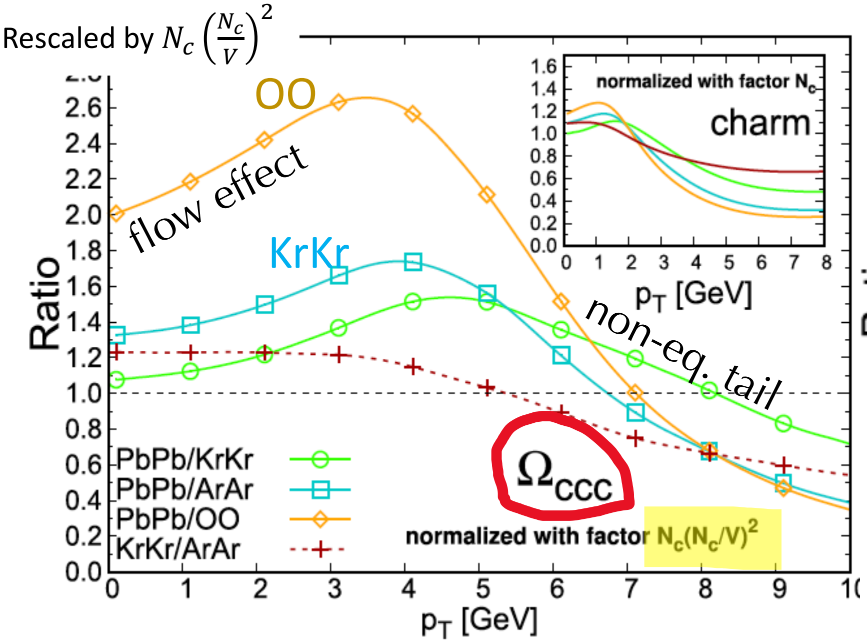
thermal full $dN_{charm}/dp_T \sim$ SHM

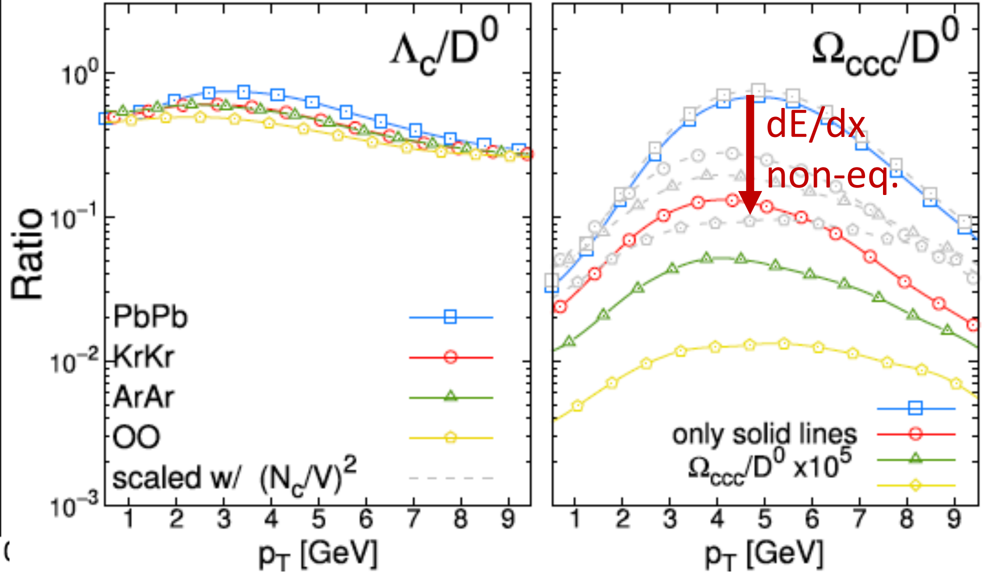
realistic dN_{charm}/dp_T from $D_s(T)$

❖ Makes a I order of magnitude difference depending on degree of equilibirum, while very small effect on D, Λ_c ~(dN_{charm}/dp_T), also due to charm # conservation & confinement

Ω_{ccc} p_T evolution from PbPb to OO

Minissale et al., EPJC84(2024)





Deviation from scaling $N_c\left(\frac{N_c}{V}\right)^2$ due to different final p_T-charm distribution wrt PbPb

Ω_{ccc} p_T spectrum evolution with system size unveil direct information of charm dN_c/dp_T with much larger sensitivity w.r.t. D^0 or Λ_c → precise info on interaction $D_s(T)$

Run 5-6 with ALICE3

Summary & Perspectives

- ❖ Open HF set up a strong connection among LQCD,NRQCD/phenomenology/exp. observables

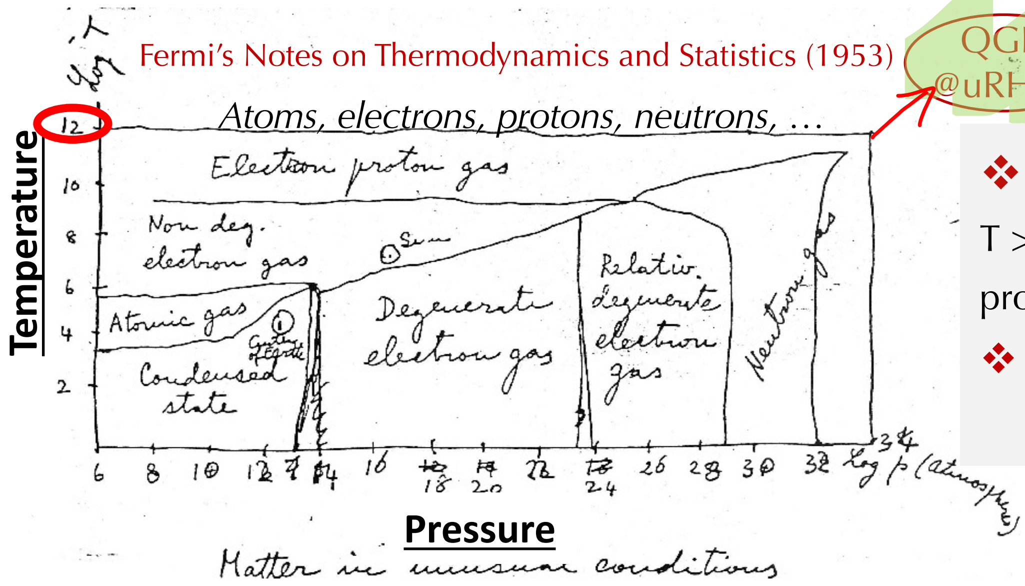
- ❖ HQ is a more sensitive probe of bulk QGP , but till now **has suffered from the lack of high statistic and access to exclusive observables**

- ❖ Precision data @*low pT* | *new observables* | *extension to bottom* | *multicharm* → breakthrough toward solid determination/understanding of:
  - interaction strength at high T; agreement phenomenology with LQCD? & close to AdS/CFT? validity of NREFT/ QCD at finite T
  - understanding HQ hadronization universal/non-universal from pp@TeV to AA *[Hadronization reveals pp@TeV as a small dense medium much closer to AA than e^+e^- !?]*

- ❖ Open HF as novel probe of Glasma studies [especially in pA]

Back-up Slide

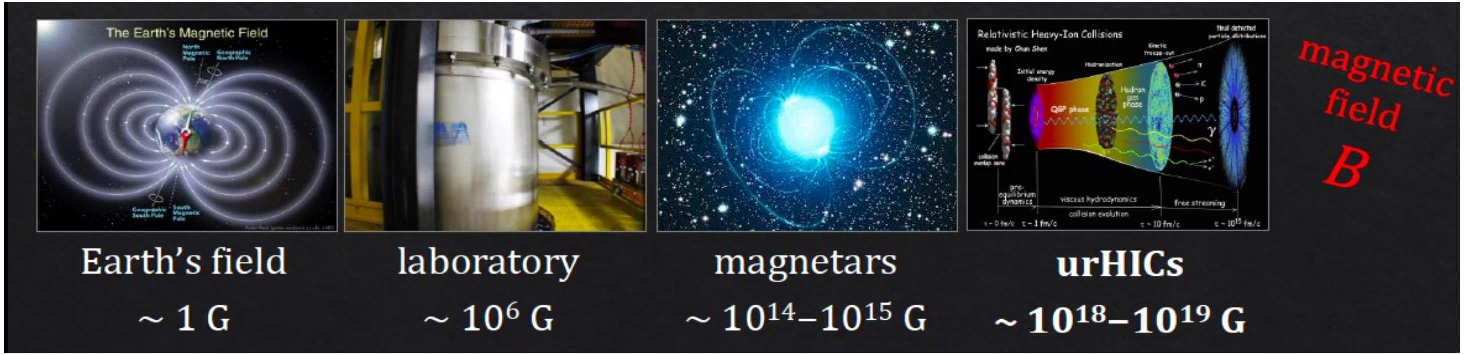
Matter under the most extreme conditions



- ❖ **Fermi put Nothing above 10^{12}K!**

$T > 10^{12}$K ≈ 200 MeV → **T= E≈1/L** → L<1 fm inside a proton, but in the '50 there was nothing inside a proton

- ❖ uRHIC creates matter with ε ~ *** , ρ ~*** but also…

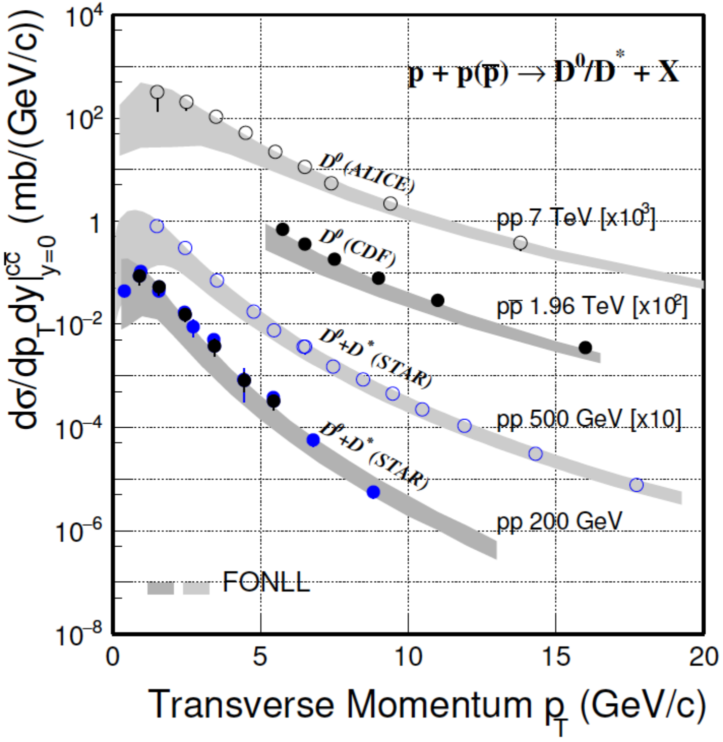


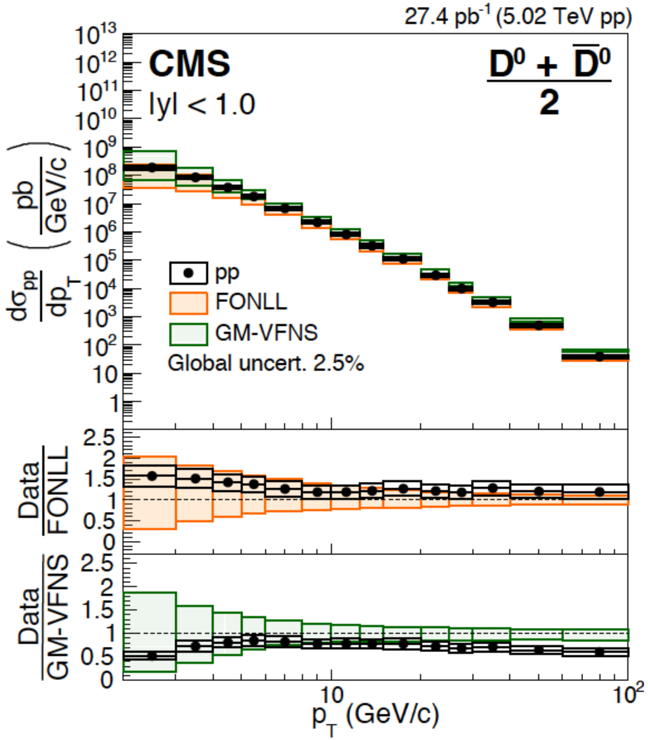
For highest vorticity

$\omega \sim 10^{22}\ s^{-1}$

F. Becattini [next talk]

Initial Production - $m_Q >> \Lambda_{QCD}$





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

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

FONNL (Fixed Order NNLO pQCD)

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

HQ link to lattice QCD at finite T

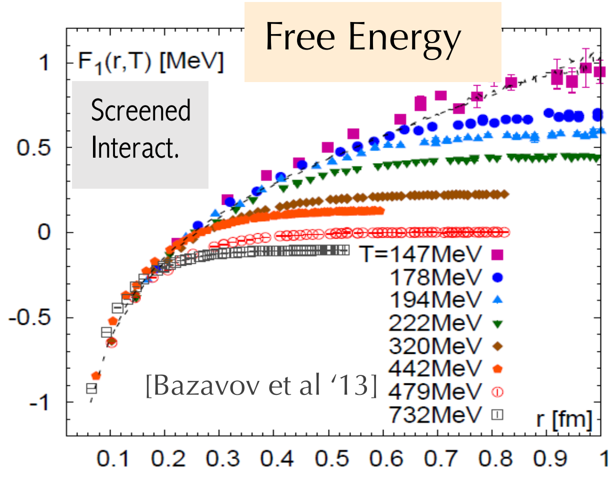
❖ **Extract the Free Energy of $\bar{Q}Q$ → NREFT/ T-matrix**

→HQ Potential F=U-TS $q_0^2 \approx \vec{q}^4 / m_Q^2 << \vec{q}^2$

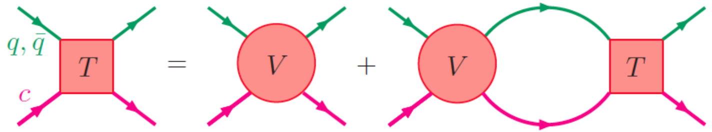
space-like transfer momenta. → V(r) + relat. corr.

low screening into full Coulomb-like

→ Theoretical approach from T-matrix linked to LQCD and/or development of NRQCD at finite T



Scattering under a potential V(r,T) derived from lQCD Free-energy:

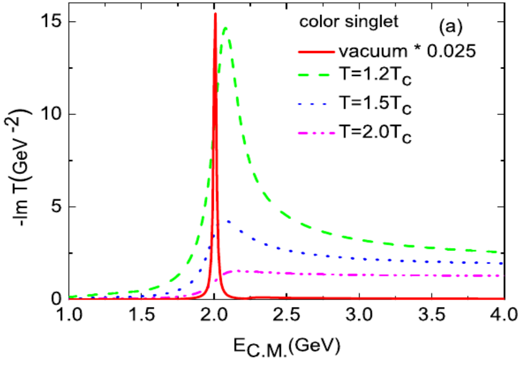


Van Hees, Greco, Rapp, PRL100 (2008)

Fit screened Cornell V(r)+ Im. part. (pert.-like ansatz)+ relativistic corr.

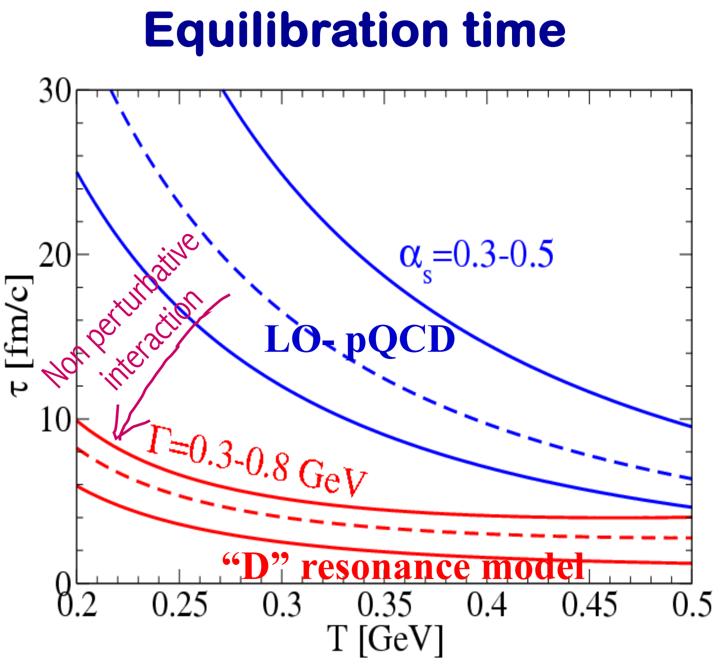
$$F_{Q\bar{Q}}(T,r) = -T \ln\left(\int_{-\infty}^{\infty} dE \, \frac{-1}{\pi} \frac{(V+\hat{\Sigma})_I(E)}{\left(E-(V+\hat{\Sigma})_R\right)^2 + (V+\hat{\Sigma})_I^2(E)} e^{-\beta E}\right)$$

[SYF Liu + Rapp, '15]

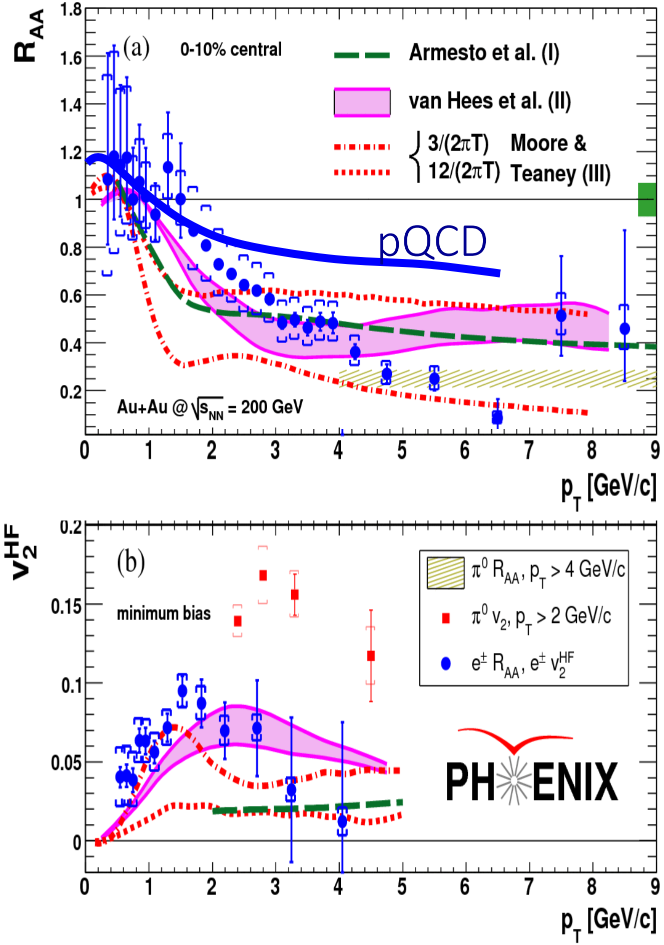


➢ Compare T-matrix $F_{Q\bar{Q}}(T,r)$ with lattice $F_{Q\bar{Q}}(T,r)$ to extract in-medium $V(r)$ and $\hat{\Sigma}$

In 2005-06 … first comparison to data



"D" Resonance model used in
Van Hees, Rapp, PRC71(05)
Van Hees, Greco, Rapp, PRC73 (06)



Relativistic Boltzmann equation at finite η/s

Bulk evolution

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

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

Free-streaming

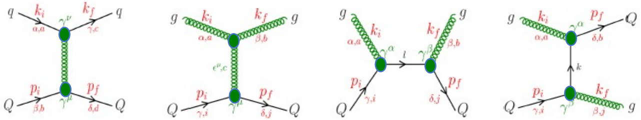
Field interaction $\varepsilon - 3p \neq 0$

Collision term gauged to some $\eta/s \neq 0$

Equivalent to viscous hydro at $\eta/s \approx 0.1$

HQ evolution

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



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

Non perturbative dynamics → M scattering matrices (q,g → Q) evaluated by Quasi-Particle Model fit to **lQCD thermodynamics**

$$m_g^2(T) = \frac{2N_c}{N_c^2 - 1}\, g^2(T)\, T^2$$

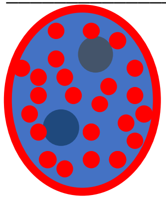
$$m_q^2(T) = \frac{1}{N_c}\, g^2(T)\, T^2$$

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

Impact of off-shell dynamics:
M.L. Sambataro et al., *Eur.Phys.J.C* 80 (2020) 12, 1140

R_{AA} & v_2 with upscaled pQCD cross section

Moore & Teaney, PRC71 (2005)



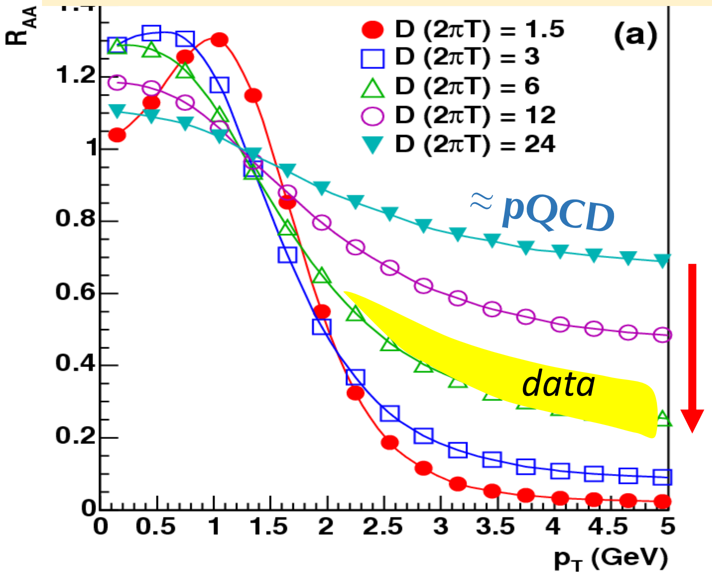
Fokker-Plank for charm interaction in a hydro bulk

Diffusion coefficient

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

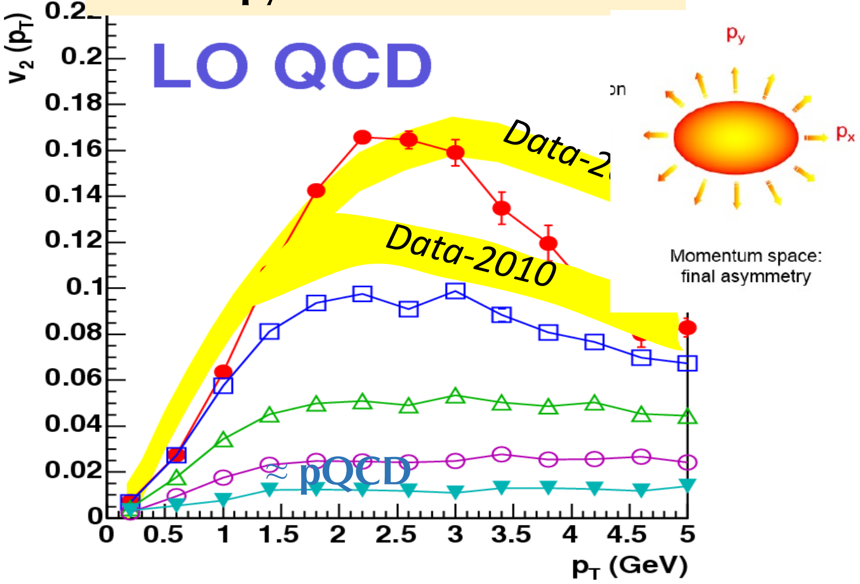
scattering matrix

Ratio normalized p_T spectra pp/AA



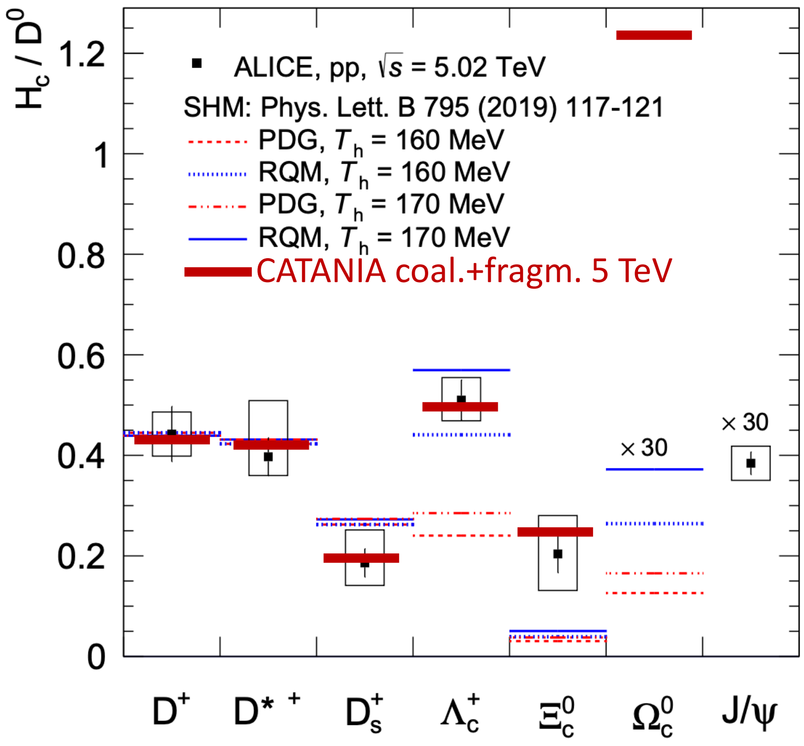
Multiplying by a K-factor pQCD

Anisotrpy Azimuthal emission



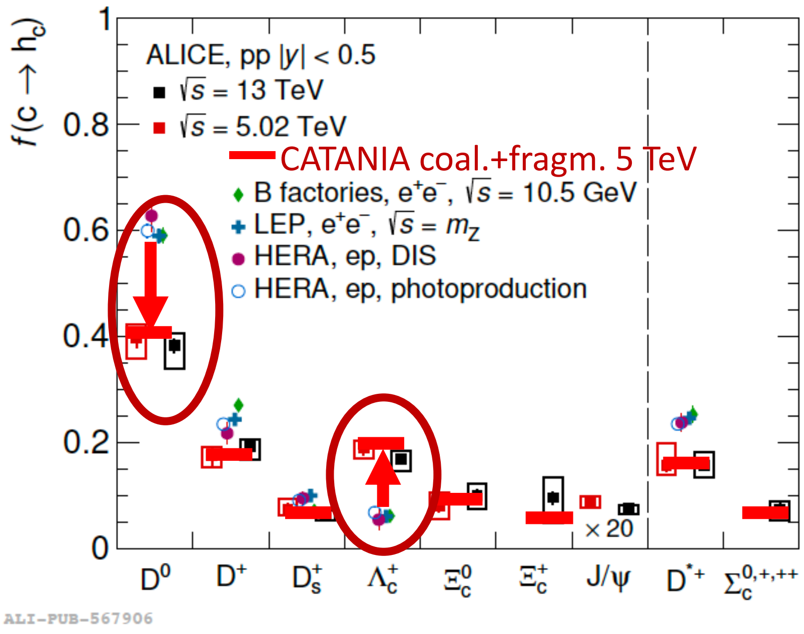
It's not just a matter of pumping up pQCD elastic cross section: too low R_{AA} or too low v_2

Ratio to D^0 in pp

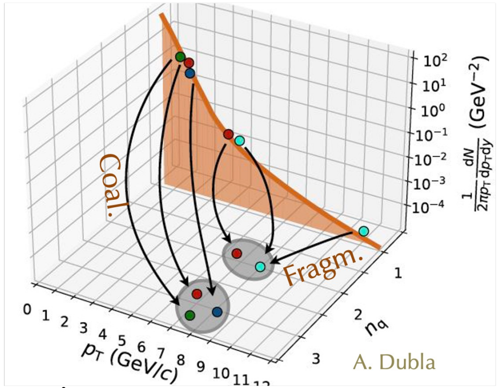


- Evidence of different "Fragmentation" Fractions in pp at LHC wrt e^+e^- & e^-p but similar to AA
- Coalesc.+Fragm. very close to pp FF
- Large Ξ_c , Ω_c only in coalescence, lack of yield in PYTHIA, SHM,…
- SHM+RQM baryon resonances would have a similar agreement (T~160-170 MeV)
  … except for Ξ_c, Ω_c
  [Andronic et al., *JHEP* 07 (2021)]

"Fragmentation" Fractions in pp Catania Coalescence



- Evidence of different "Fragmentation" Fractions in pp at LHC wrt e^+e^- & e^-p but similar to AA
- Coalesc.+Fragm. very close to pp FF
- Large Ξ_c , Ω_c only in coalescence, lack of yield in PYTHIA, SHM-RQM,…



Seems only hadronization models treating pp as a small QGP fireball or allowing allowing local reconnection-recombination get close to data..

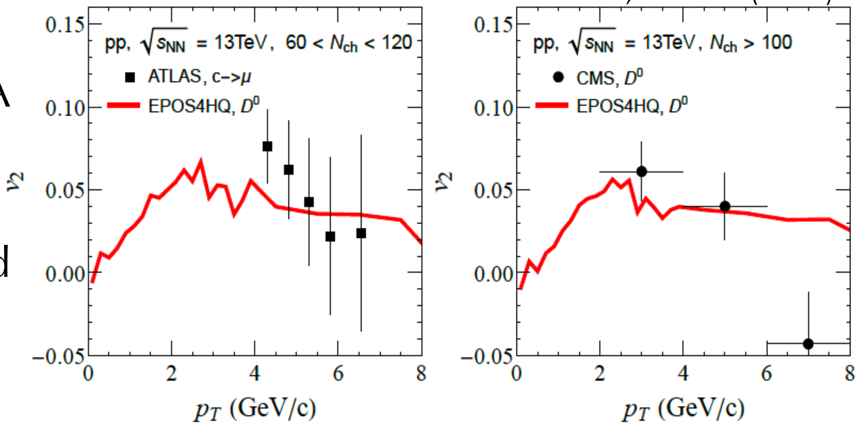
HF coalescence in EPOS4HQ

- ➢ <u>Advantages of implementing coal. in EPOS4</u>:
- Full dynamical realistic dynamics from ep, pp to AA
- **Able to predict also a sizeable elliptic flows**
  → more solid costraints to hadronization
  and the properties of the pp QCD matter created

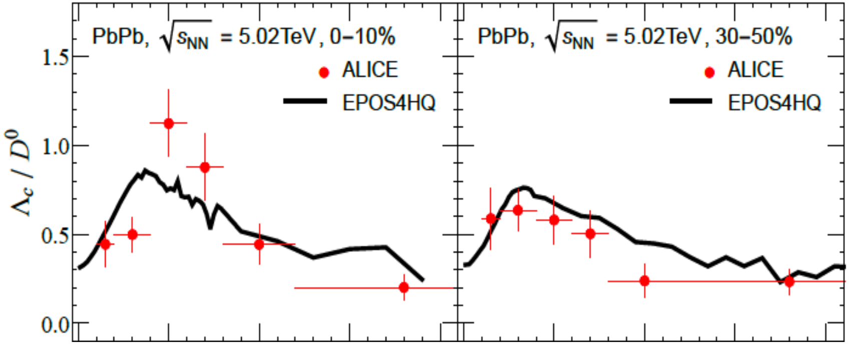
  → $v_2(\Lambda_c)/v_2(D^0)$ would give more insight into coal.

➢ Would PYHTIA-CR predict finite v_2 of D, Λ_c in pp? String shoving?

J.Zhao et al., PRD109 (2024)

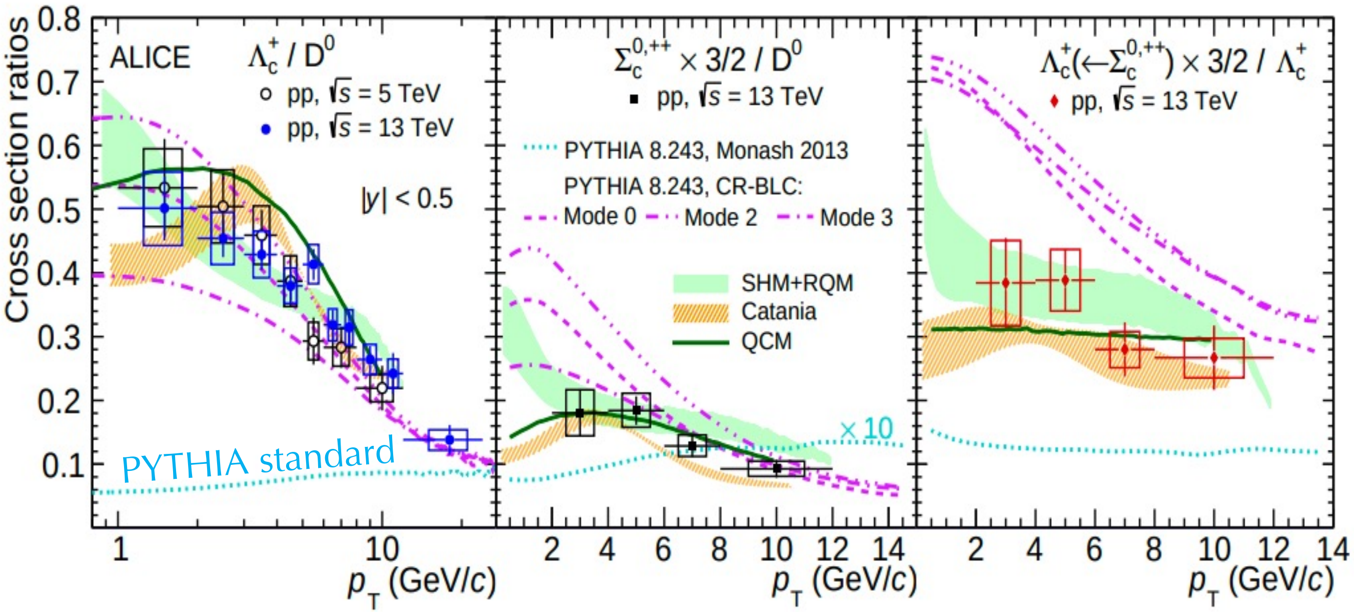


Extension to AA and bottom,
J. Zhao et al. arXiv:2401.11275



Going deeper into Λ_c enhancement

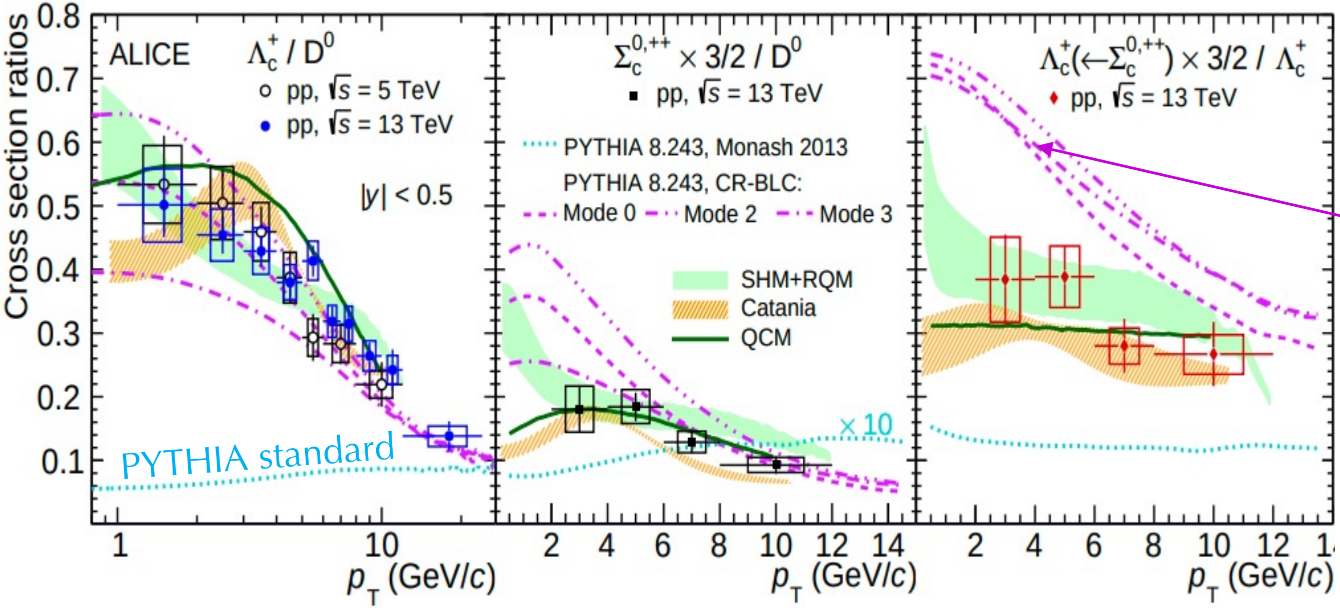
Altmann et al., arXiv 2405.19137

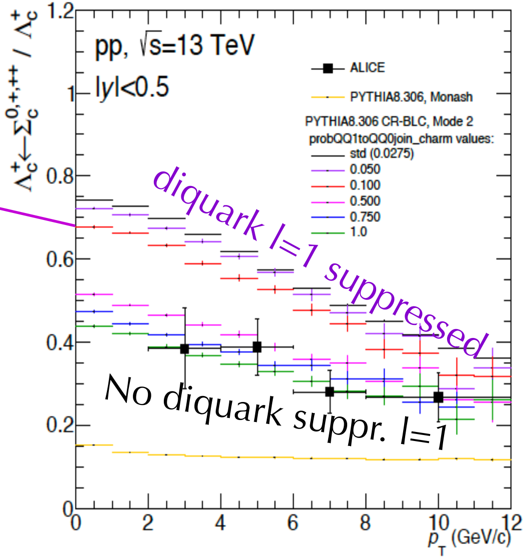


- Catania-coal & SHM-RQM/QCM natural good description of Σ_c/D^0 and $\Lambda_c \leftarrow \Sigma_c$
- PYTHIA-CR too many $\Sigma_c \rightarrow \Lambda_c/D^0$

Going deeper into Λ_c enhancement

Altmann et al., arXiv 2405.19137

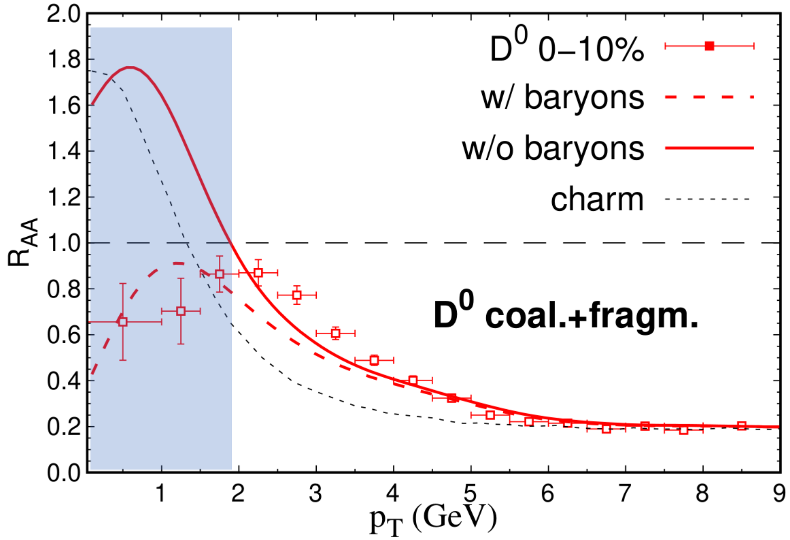


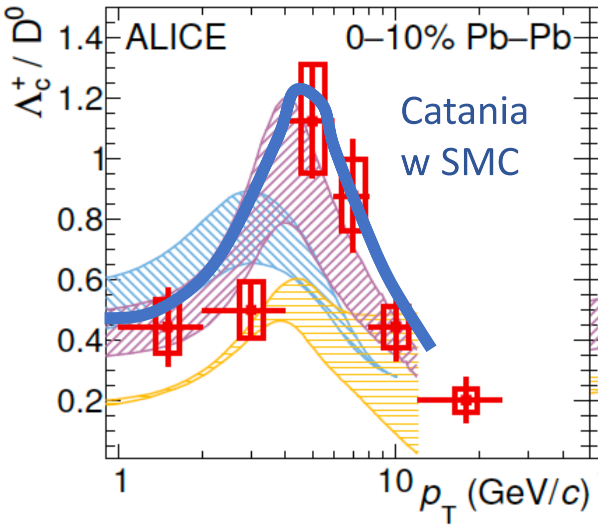


- Catania-coal & SHM-RQM/QCM natural good description of Σ_c/D^0 and $\Lambda_c \leftarrow \Sigma_c$
- PYTHIA-CR too many $\Sigma_c \rightarrow \Lambda_c/D^0$; associated to a suppression of junction **diquark *I=1*** *(set ~* e^+e^- for string di-quark*). Removing it →Agreeement to data of* $\Lambda_c \leftarrow \Sigma_c$

It goes in the direction of simply recombine according to SU(3) ~ simple colaescence

HF Baryon enhancement: impact on R_{AA}





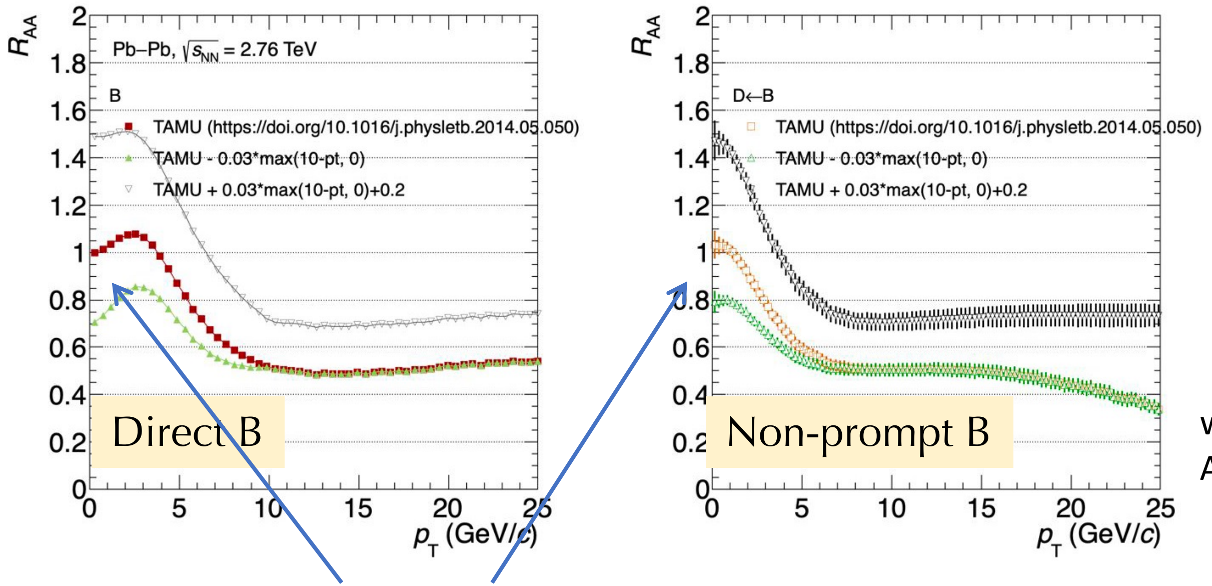
Λ_c production was mostly neglected in the first studies of R_{AA}, but:

- Strong impact on R_{AA} low-intermediate p_T →affect estimates of D_s
- Stronger coalescence → smaller Ds
- $\Lambda_c/D \sim O(1)$ already in pp@TeV: pp ~ AA ≠ e^+e^-, e^-p

HF Hadronization in jet shower – [S. Sadhu- this session]

Relevance of direct Bottom measurements

Just an first example, for the more plain observable R_{AA}….



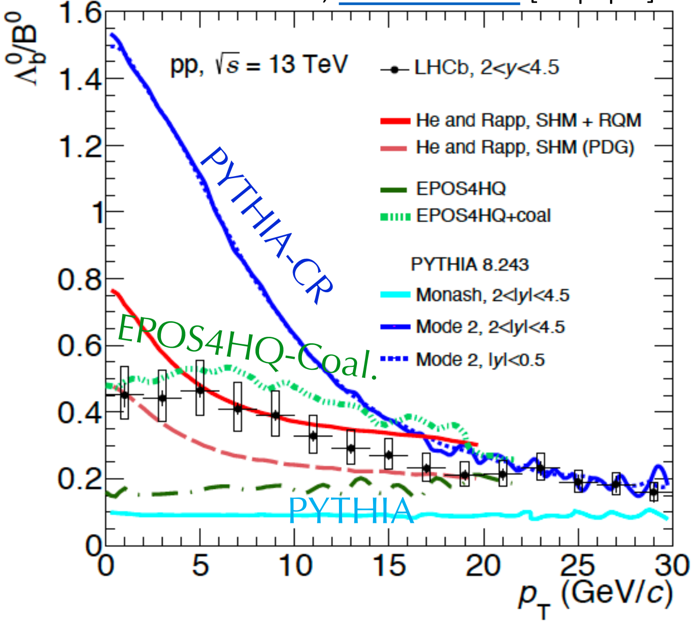
workshop on QCD challenges from pp to AA collisions, Sept. 2024

Peak depends on the degree of b coupling to QGP medium is smeared-out in non prompt measurements

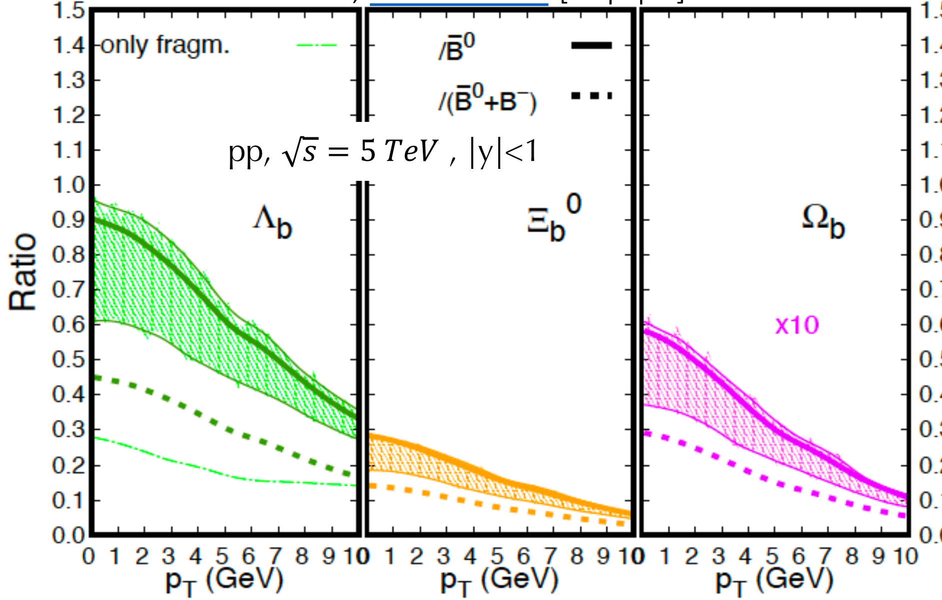
Direct B, L_b measurement at low p_T → need for Runs5-6

Early results and predictions for Bottom in pp

Altmann et al., 2405.19137 [hep-ph]



V. Minissale et al., 2405.19244 [hep-ph]



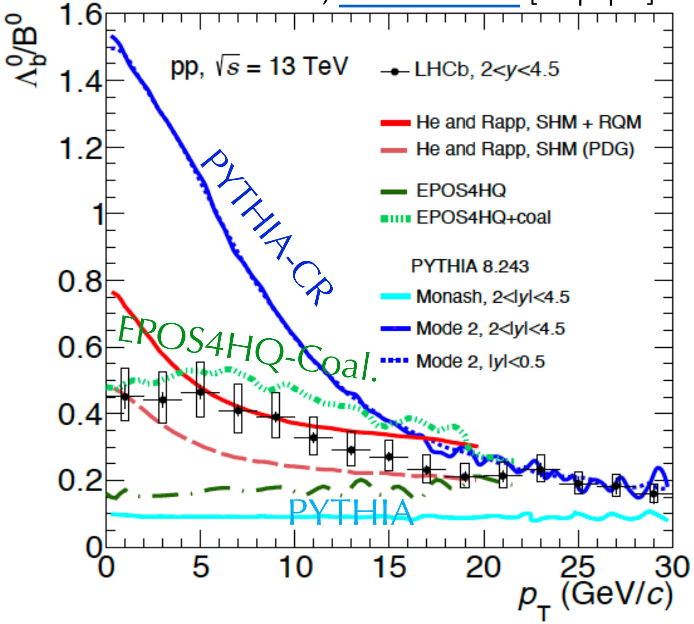
Plumari, Tue 4-[9:10]

- Again Need CR in PYTHIA→ seems too strong at forward (no rapidity dependence)
- EPOS4HQ**+coal** close to data (rapidity dependence?). At y=0 Catania results
- SHM +RQM about close, less the p_T shape (Frag.-Function)
- Coal./Fragm. ratio in pp larger for B than D

Slide su importanza large rapidity coverage

Figura Lc/D a rapidita finita

Altmann et al., 2405.19137 [hep-ph]

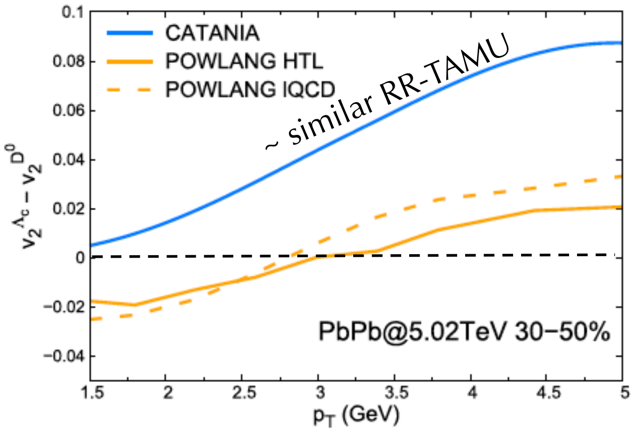


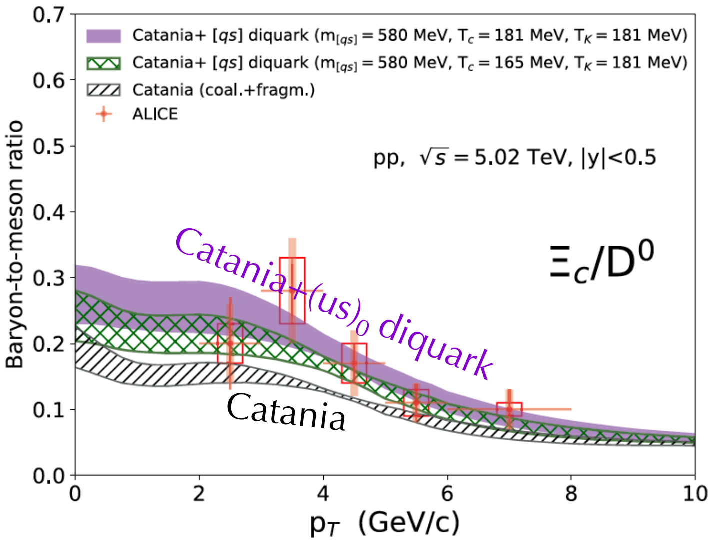
Strong adavantage to see the evolution with rapidity in the same system
- Disentangle size and parton density impact

Impact of diquark?

QCD challenges from pp to AA, EPJC 84(2024)

- ❑ Coal. Approaches (*Catania, LBT, EPOS4HQ… RR-TAMU*)
  ➔ $\mathbf{v_2(\Lambda_c) > v_2(D^0)}$ at $p_T > 2$ GeV
  because Λ_c gets flow from 2 light quarks, D^0 from 1+fragm.
- ❑ POWLANG assume diquark hydrodynamical flow and
  Λ_c=(qq)+c -> $v_2(\Lambda_c) \sim v_2(D^0)$ at intermediate p_T





- ❑ Quark model gives $(us)_0$ large binding energy →small mass.
  If V(r,T) potential at finite T with large m_D ~ LQCD
  Assumption:
  - Again $(us)_0$ thermal yield flowing with the medium

* More precise data needed to draw any conclusion
→ may be Run 4

H. Yun, S.H. Lee et al., PLB 851(2024)

an elephant in the liquid

Memory effect? Non-Markovian dynamics

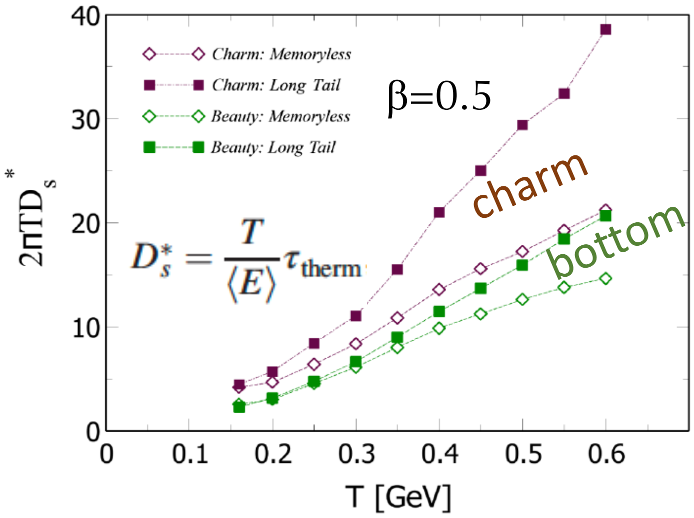
Pooja et al., PRD108(2023)

Generalized Langevin equation

$$\frac{dp(t)}{dt} = -\int_0^t dt' \gamma(t,t') p(t') + \eta(t)$$

$$\langle \eta(t_1)\eta(t_2)\rangle = \frac{\mathcal{D}}{\tau}\langle h(t_1)h(t_2)\rangle,$$

$$\langle h(t_1)h(t_2)\rangle \cong \kappa \left(\frac{t_1}{\tau}\right)^{\beta-1}\left(\frac{t_2}{\tau}\right)^{\beta}$$



There could be correlations in the initial glasma and toward the phase transition

- Exponential memory function t ~ 1 fm/c → not significant final effects. In many area of physics and chemistry there power law function

M. Ruggieri et al., PRD 106(2022)

Memoryless $\langle p_x\rangle = \langle p_{x0}\rangle e^{-t/\tau_{therm}}$ starting from FONNL checking that it leads to same Υ_{therm} =K/K_{eq} for different D

For memory we look at the same Υ_{therm} to estimate τ_{therm}

For bottom even a very strong memory function leaves the estimate of D_s nearly unaffected

$$\tau \ll \tau_{therm} \sim 5 - 10\ fm/c$$

Expected a smaller D_s to reproduce similar R_{AA}

Extension to higher order anisotropic flows $v_n(p_T)$

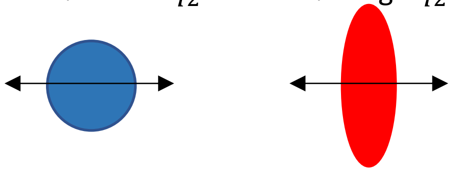
ESE tecnique and v_n correlations

Selection of events with the same centrality but different initial geometry on the basis of the magnitude of the second-order harmonic reduced flow vector q_2.

$$q_2 = |\vec{Q}_2|/\sqrt{M}$$

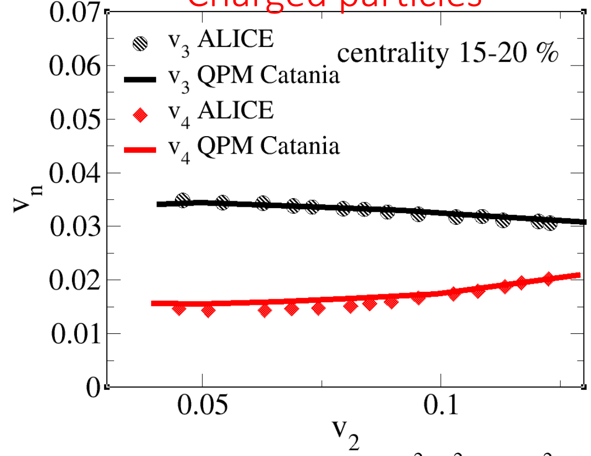
$$\vec{Q}_2 = \sum_{j=1}^{M} e^{i2\varphi_j}$$

20 % small q_2 20 % large q_2

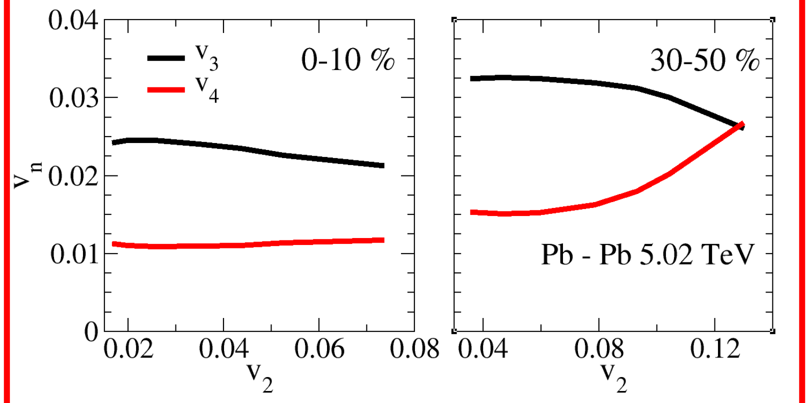


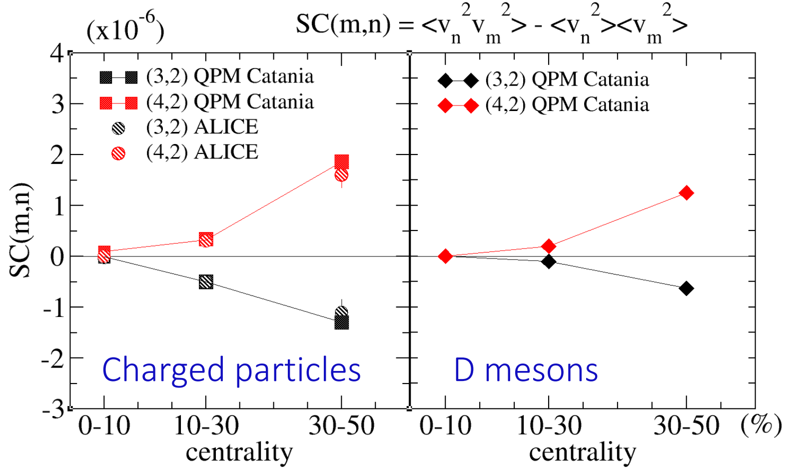
Large $q_2 \rightarrow$ large ε_2

Charged particles



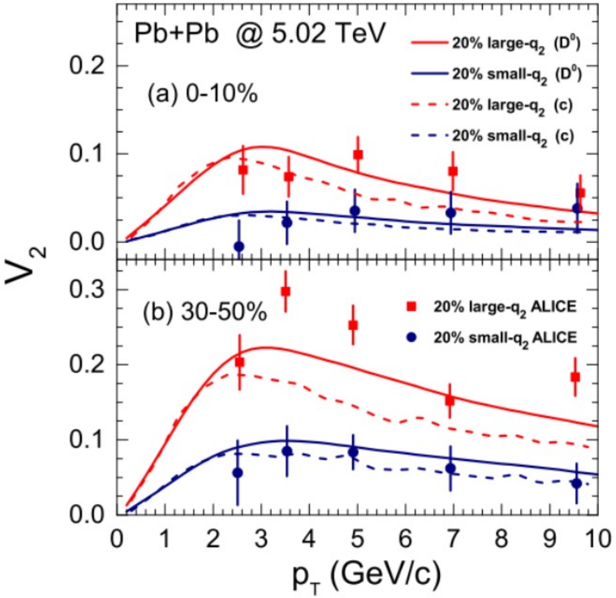
Predictions for D mesons



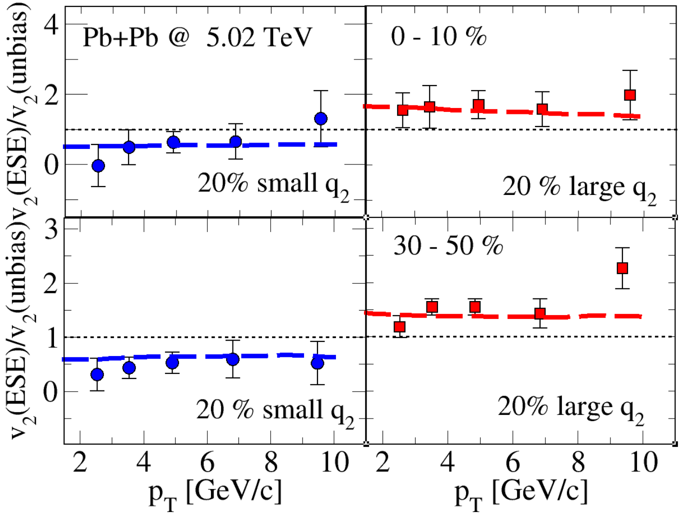


ESE: v_2 and spectra (20% small/large q_2)

$q_2$selected $v_2(p_T)$



$q_2$selected $v_2(p_T)$ ratio

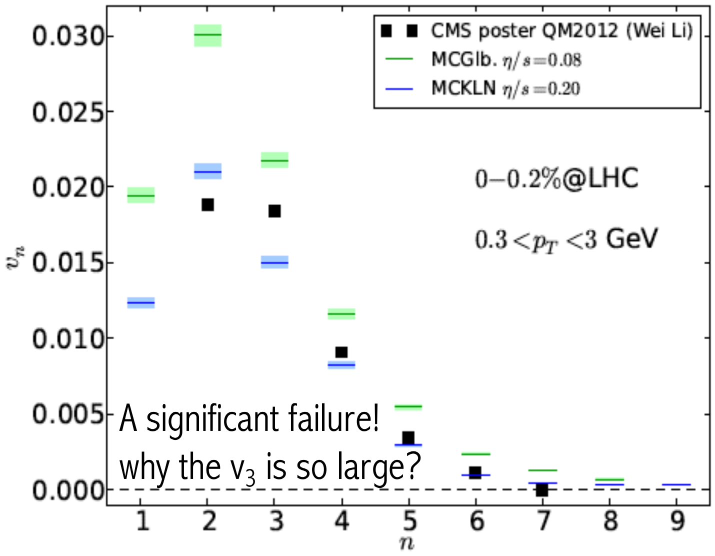


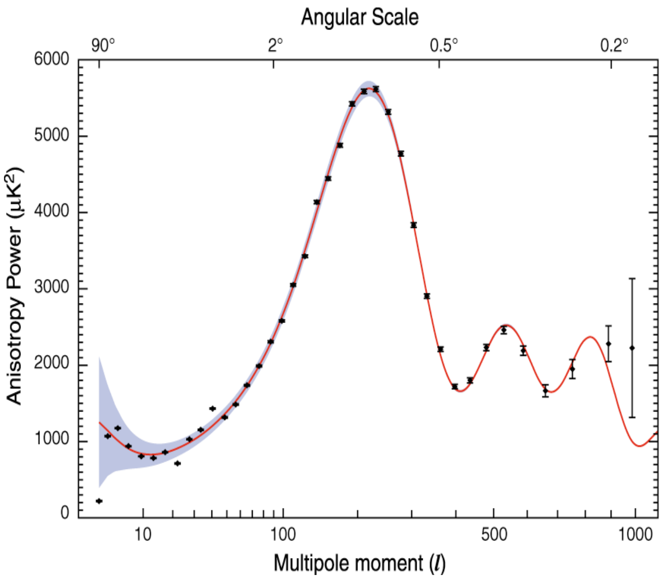
Data taken from ALICE collaboration: *Phys.Lett.B* 813 (2021) 136054

- v_2 (large- q_2 /small- q_2) ≷ v_2 (unbiased) of about 50% in both 0-10% and 30-50% centrality
- The standard approach for R_{AA} and v_2 works for ESE observables

Y. Sun et al. in preparation

Going deeply into Hot QCD matter





- Initial QCD quantum fluctuations
- T dependence of η/s
- Equation of State
- Freeze-out dynamics

Keeping size and time of QGP

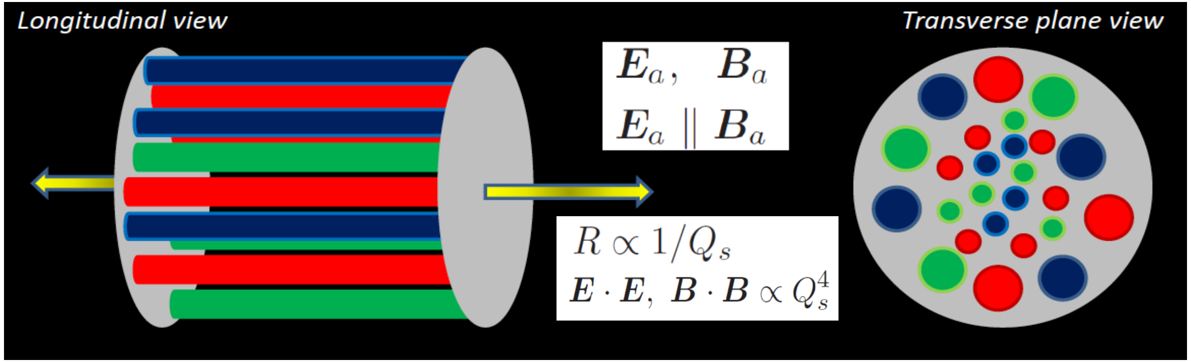
- Standard Model Matter
- Cold Dark Matter
- Dark Energy
- Hubble Constant

Keeping Age and Flatness of the Universe

Possible because at LHC one starts to create about than 10,000 particle per event

A first study of HQ in a Glasma

What happens for 0⁺<t<0.3-0.5 fm/c?



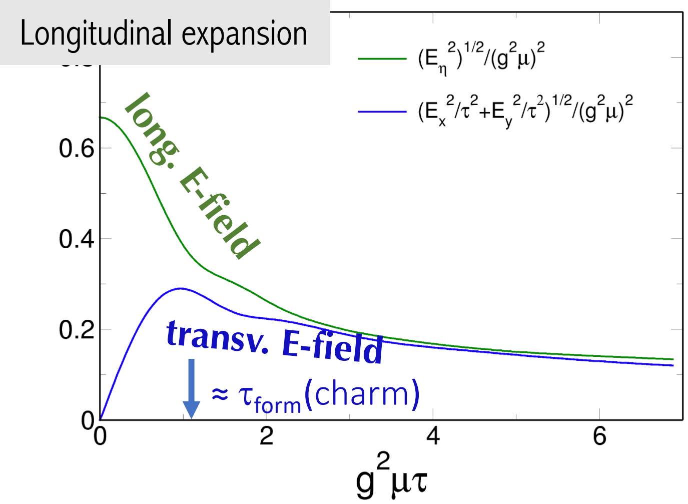
$$\langle \rho_A^a(x_T)\rho_A^b(y_T)\rangle = (g^2\mu_A)^2\delta^{ab}\delta^{(2)}(x_T - y_T),$$

Inizialization by Mc-Lerran/Venugopalan model PRD49(1994)

$$\frac{dA_i^a(x)}{dt} = E_i^a(x), \quad (16)$$

$$\frac{dE_i^a(x)}{dt} = \sum_j \partial_j F_{ji}^a(x) - \sum_{b,c,j} f^{abc} A_j^b(x) F_{ji}^c(x). \quad (17)$$

Longitudinal expansion



Formation time of transverse E-B fields $g^2\mu\tau \approx 1 \approx \tau_{form}$(charm)

after $\tau \cong Q_s^{-1}$, all components are equal

The very early stage has left some imprints?

J. Liu, S. Plumari, K. Das, M. Ruggieri, VG, Phys. Rev. C 102 (2020) 4, 044902

Role of HQ also in the CGC/Glasma studies

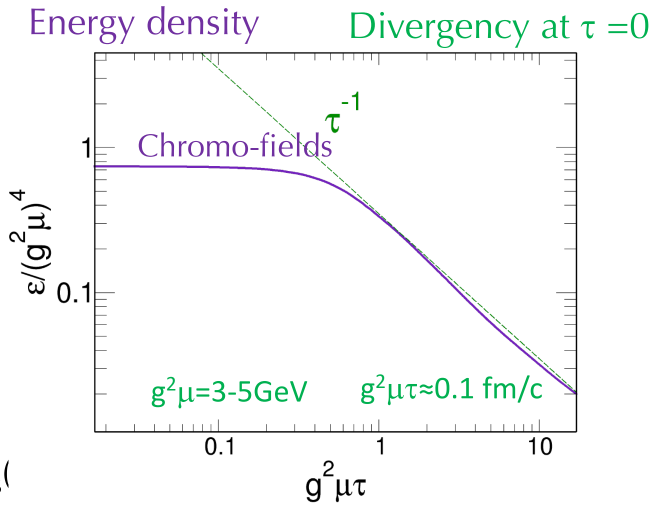
- HQ dynamics starting from $\tau_0 \approx 1/2m_Q \approx 0.02\text{-}0.08$ fm/c

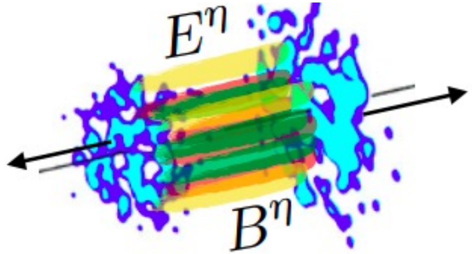
- Relevance to HQ in pA collisions

  → Explain R_{pA} ~ 1 and large v_2 of D meson
  → may have a key role on D-$\underline{D}$ angular correlation

- May affect the determination of $D_s(T)$

  → modify (improve) the relation R_{AA} & v_2 toward a smaller $D_s($

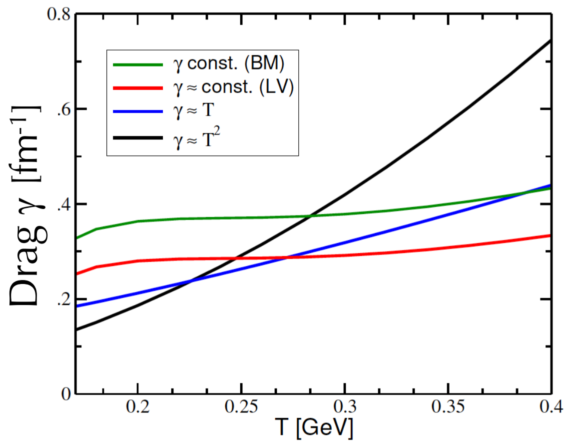




A substantial goal for HL-LHC …

The issue is not that the unknown early stage would destroy our current picture, but to find signatures from the early stage dynamics (~ for Early

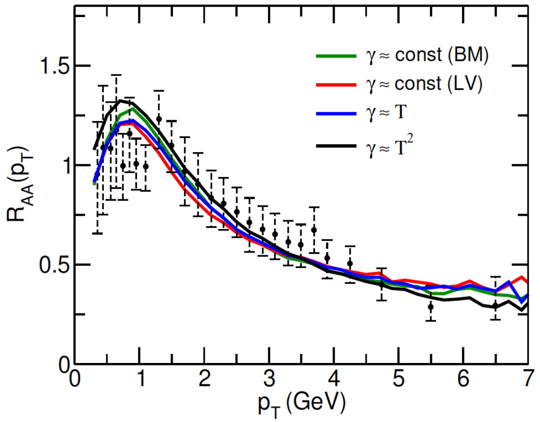
Impact of T dependent interaction on $R_{AA} - v_2$

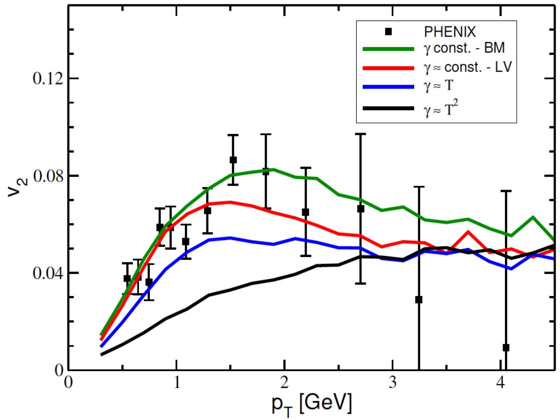


Looking at it beyond the specific modelings

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

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

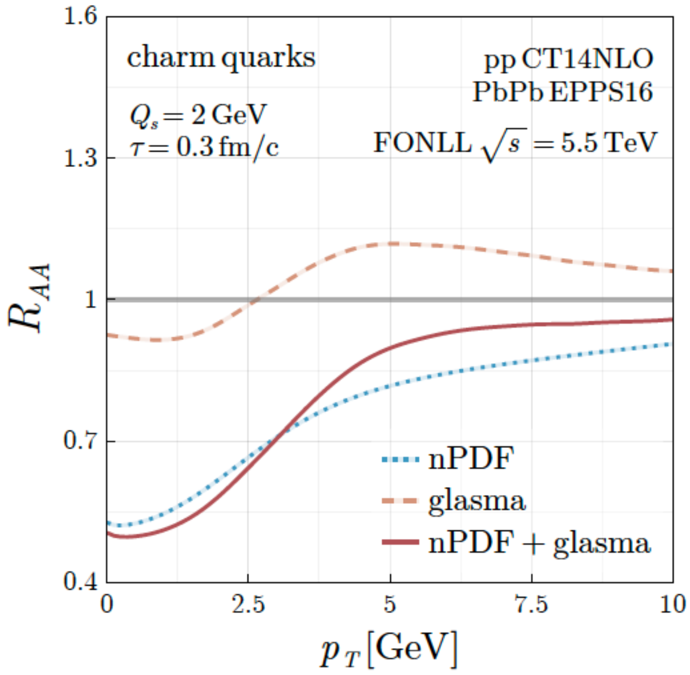




More sensitivity of charm interaction than light quarks (bulk QGP) :

→ a sign of larger τ_{therm} advantage of slower thermalization wrt to light q

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


charm quarks
$Q_s = 2$ GeV
$\tau = 0.3$ fm/c
pp CT14NLO
PbPb EPPS16
FONLL $\sqrt{s} = 5.5$ TeV
nPDF
glasma
nPDF + glasma
R_{AA}
p_T [GeV]
1.6
1.3
1
0.7
0.4
0
2.5
5
7.5
10

Chiral Magnetic Effect and P &CP violation

Axial current j^5_μ : net handedness flow

$$\partial^\mu j^5_\mu = 2\sum_f m_f \langle \bar{\psi}_f i\gamma_5 \psi_f \rangle_A - \frac{N_f g^2}{16\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a,$$

A **sphaleron** drives locally a chiral imbalance

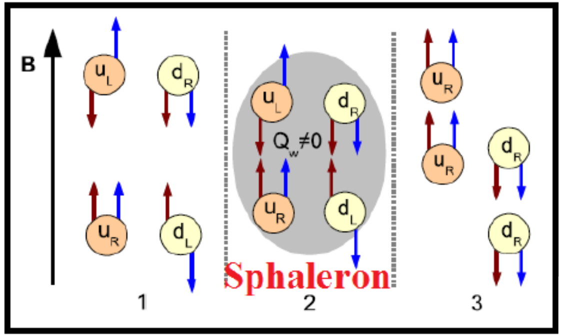
$\langle N_L - N_R \rangle \neq 0$ in HotQCD matter

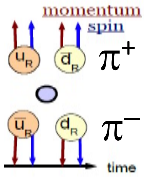
Reveals a **local Parity breaking in Strong Interactions**

Consider a homogeneous, strong magnetic field (Warringa, 2008):

Momentum

Spin





$$(N_L - N_R)_{+\infty} - (N_L - N_R)_{-\infty} = 2Q_W$$

A local axial $\mu_5 = \mu_R - \mu_L$ (topological μ_θ) induces an electric current J_v along B → charge separation

No *C*-odd but *CP*-odd

$$j_V = \frac{N_c\, e}{2\pi^2}\mu_A \mathbf{B}$$

P-odd current absent in Maxwell eq.s driven by axion field

Expected exp. effect: dipole modulation of azimutal distribution

$$\frac{dN_\pm}{d\phi} \sim 1 + 2v_1\cos(\Delta\phi) + 2v_2\cos(2\Delta\phi) + \cdots + 2a_\pm \sin(\Delta\phi)$$

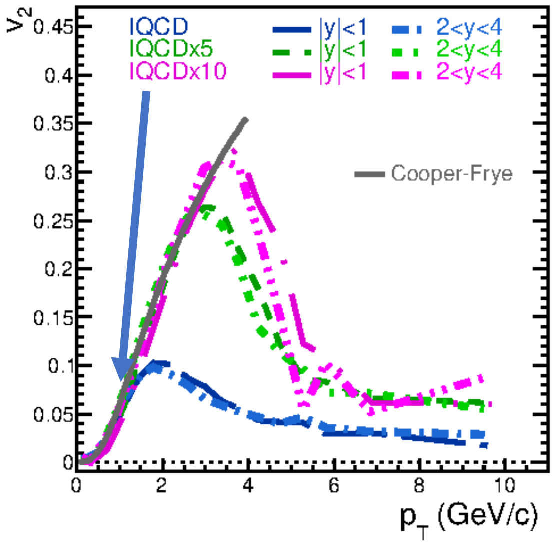
CME

Relaxation time of topological charge $m_q^{-1} \gg \tau_{fireball}$

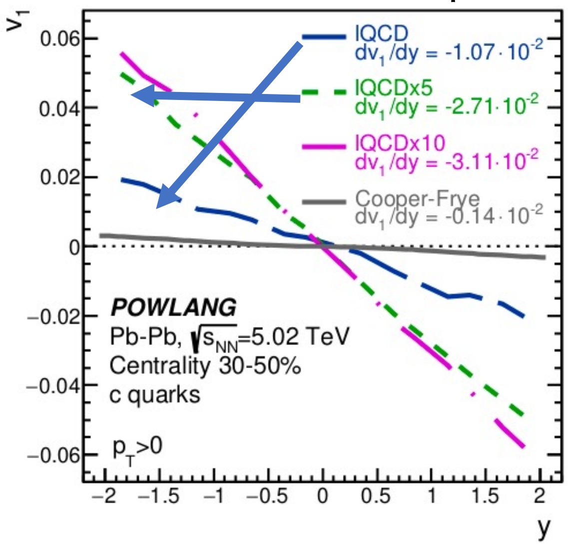
Observed in Dirac semi-metals – Q. Li et al., *Nature Physics* 12 (2016)

v_1 large sensitivity in the low p_T

v_2 not sensitivite to D_s value at low p_T



v_1 much more sensitivity to D_s value at low p_T

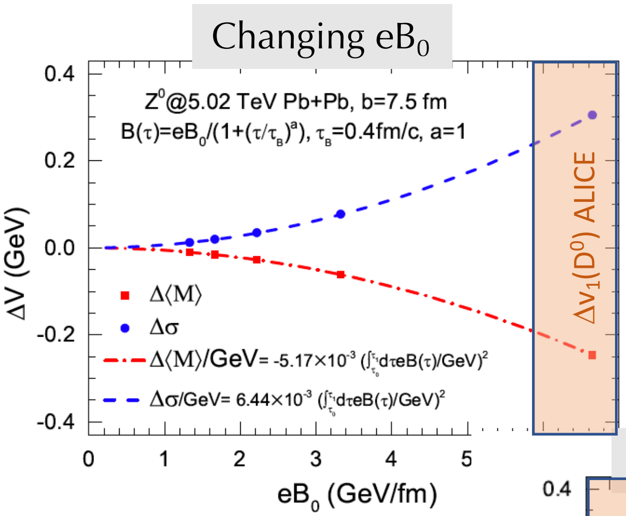


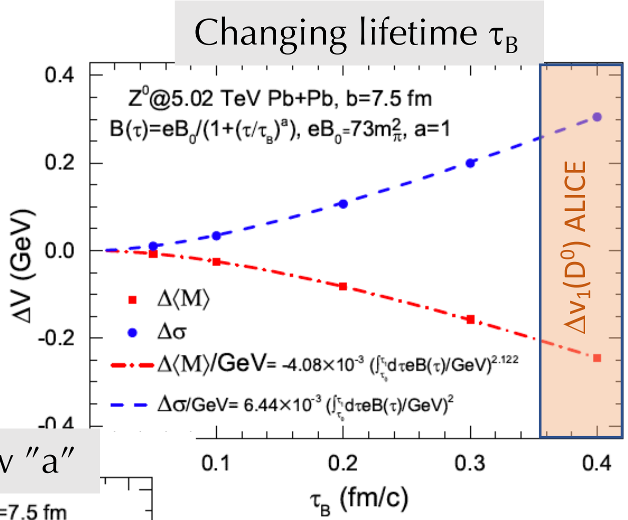
Run 4 for |y|<1 or 2 (CMS)
Run 5-6 for |y|<4

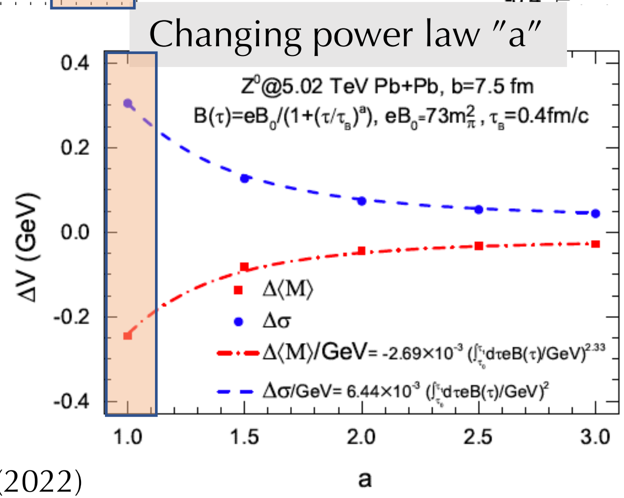
A.Beraudo et al., JHEP 05 (2021)

Observables sensitive to spatial inhomogeneity of HQ distribution, like the transverse flow v1, can provide a richer information on HF transport coefficients

Z^0 mass and width modification in AA







$$\Delta\langle M\rangle = k\left(\int_{\tau_0}^{\tau_1} d\tau\, e\, B(\tau)\right)^n$$

n=2.16±0.16

k=-[2.69-5.17] · 10^{-3}

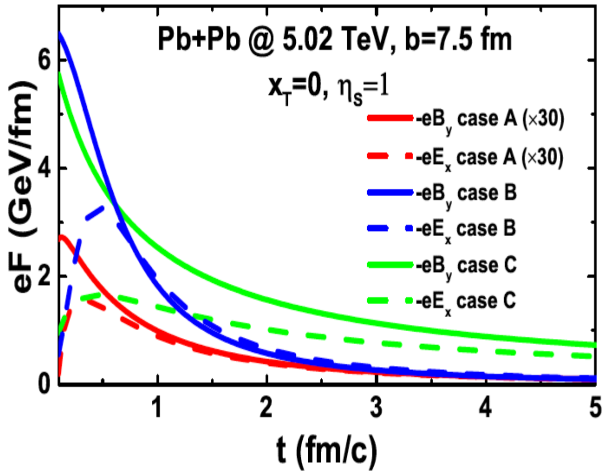
$$\Delta\sigma_{Z^0} = k_\sigma\left(\int_{\tau_0}^{\tau_1} d\tau\, e\, B(\tau)\right)^2$$

k_σ= 6.44 · 10^{-3}

Y.Sun, V. Greco, X.N. Wang, PLB 827(2022)

To be done vs centralities, systems,…

E.m. field: a main source of uncertainty



Case A

E-B fields like Gursoy et al., PRC89(2014)

Medium at t<0 + eq. medium σ_{el}=0.023 fm^{-1}

Case B and C

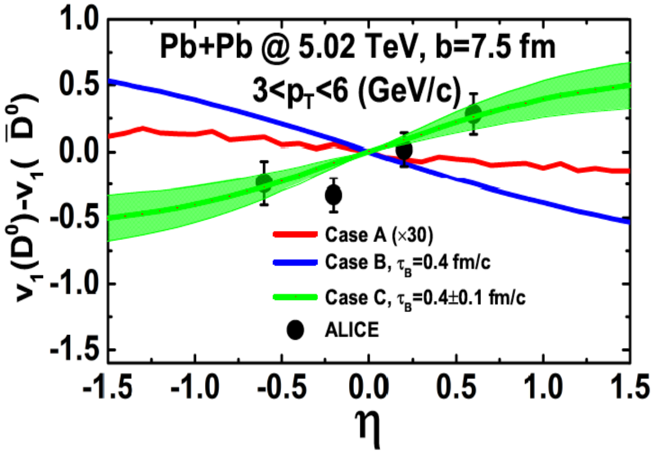
$eB_y(x,y,\tau) = -B(\tau)\rho_B(x,y)$ τ_B=0.4 fm/c

$B(\tau) = eB_0/(1+\tau^2/\tau_B^2)$

$B(\tau) = eB_0/(1+\tau/\tau_B)$

$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$: assumption $\frac{\partial E_z}{\partial x} \approx 0$ *small*

B an C similar B_y up to t< 1 fm/c



* e.m. field σ_{el} as for RHIC

→ $\Delta v_1(D^0)$ order magnitudes smaller than ALICE data + opposite sign

* e.m. with B_y(t=0) as in vacuum

→ Large $\Delta v_1(D^0)$ but **opposite** direction

* e.m. with B_y(t=0) as in vacuum, $\mathbf{E_x \approx 0.5\, B_y}$ (t=0.5-1 fm/c)

→ $\Delta v_1(D^0) \approx$ ALICE Data (1/t ideal MHD)

Time derivative of B_y(t) even more relevant than absolute values"

If $\Delta v_1 = v_1(D^0) - v_1(\underline{D}^0)$ is of electromagnetic origin → we'd have a proof of the formation of the QGP

Is there some complementary way of proving it?

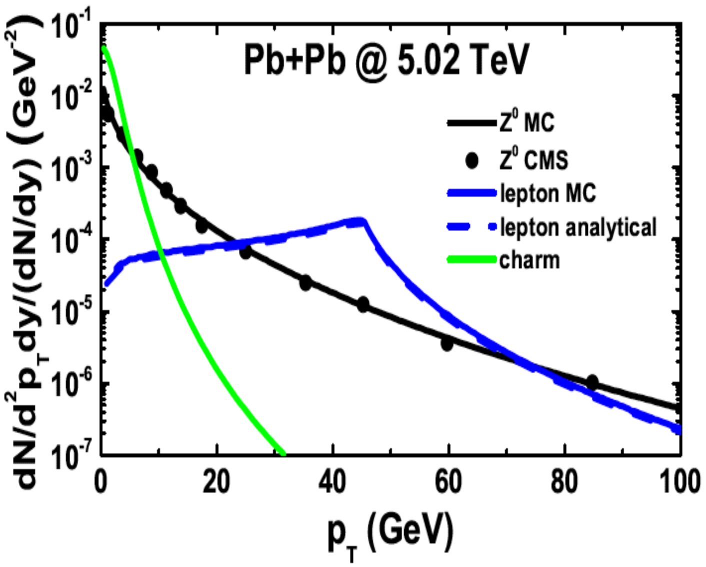
Is there a further way to pin down the e.m field strength?

Such a large splitting (in ALICE) has an electromagnetic origin?

Probing the electromagnetic fields in ultra-relativistic collisions with leptons from Z_0 decay and charmed mesons

Why leptons from Z^0?

$\tau_{Z^0} = 1/2m_{Z^0} = 0.0011\ \mathrm{fm}/c$



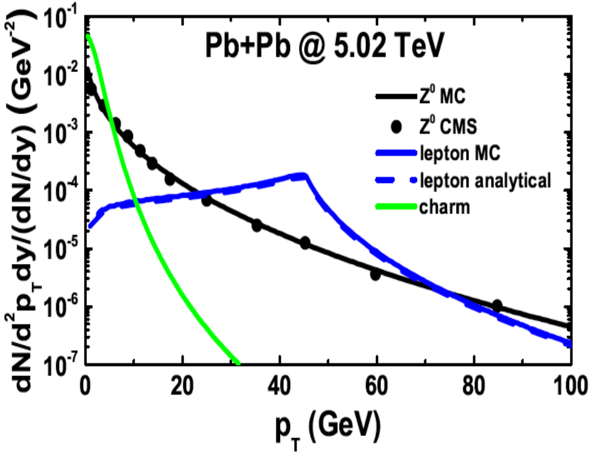
What one expects?

- No damping from medium interaction
- Massless more easily to drag
- Charge 1.5 times larger

One expects same sign and $\Delta v_1(l^+,l^-) > \Delta v_1(D^0,\underline{D}^0)$?!

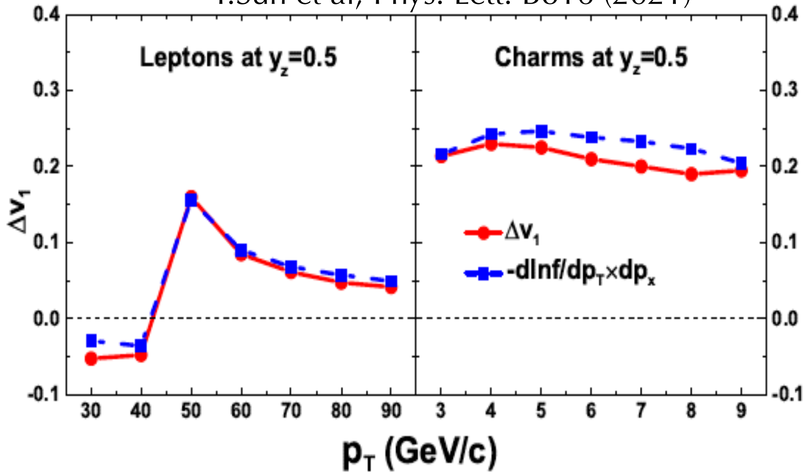
- Leptons from Z^0 decay are separable by other sources
- **$\tau_{decay}(Z^0)= \tau_{form}$(charm)=0.08 fm/c**: they go through the e.m. fields at the same time
  → meanfigul look at the correlation $\Delta v_1(D^0,\underline{D}^0)$ and $\Delta v_1(l^+,l^-)$

V_1 splitting for D^0-$\underline{D}^0$ and l^+- l^- from Z^0 decay and



- No medium strong interaction
- $\tau_{decay}(Z^0) = \tau_{form}(charm) = 0.08$ fm/c
- Massless more easily to drag
- Charge 1.5 times larger

Y.Sun et al, Phys. Lett. B816 (2021)



<u>Surprises</u>:

1) $\Delta v_1(l^+,l^-) < \Delta v_1(D^0,\underline{D}^0)$ even if $\Delta p_X(l) \approx 2^* \Delta p_X(D)$

2) even the sign of Δv_1 (l^+,l^-) can be opposite!?

not because wins electric field

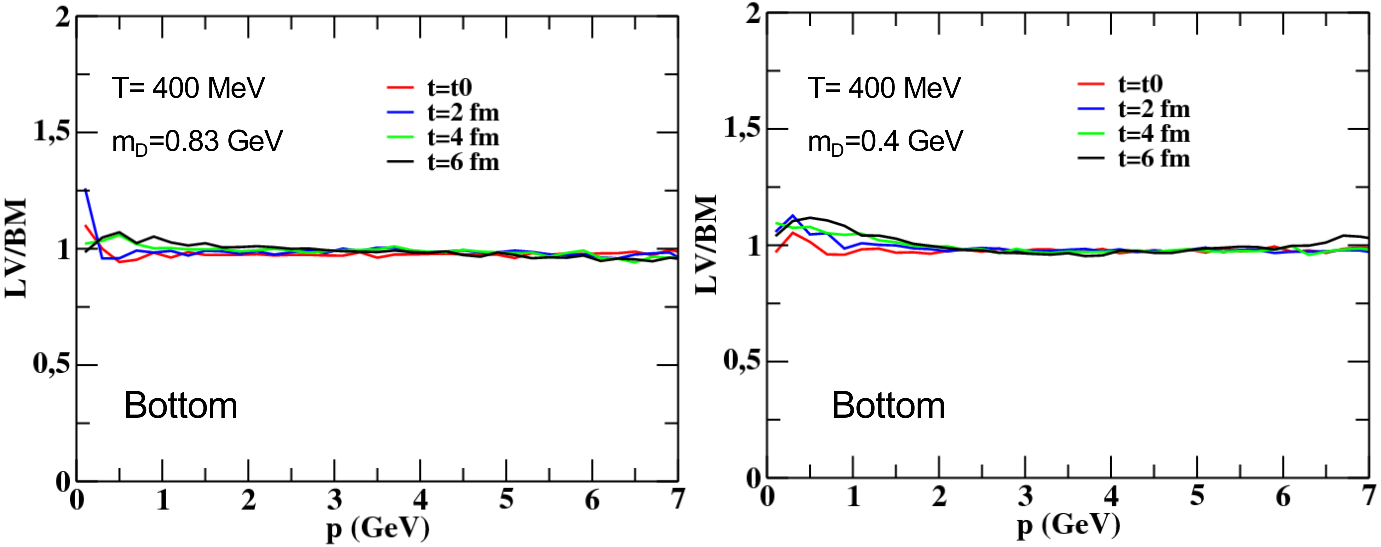
$$v_1(p_T, y) \approx \frac{\overline{\Delta p_x}(p_T, y)}{2} \frac{-\partial \ln f_a}{\partial p_T}.$$

Δp_X is always positive:
≈ 0.3 GeV for D charm
≈ 0.7 GeV for leptons
with a weak p_T dependence

Peak in $\Delta v_1(l^+,l^-)$ at $p_T \approx 50$ GeV
consistent with the large $\Delta v_1(D^0)$?

Bottom R_{AA}: Boltzmann = Langevin

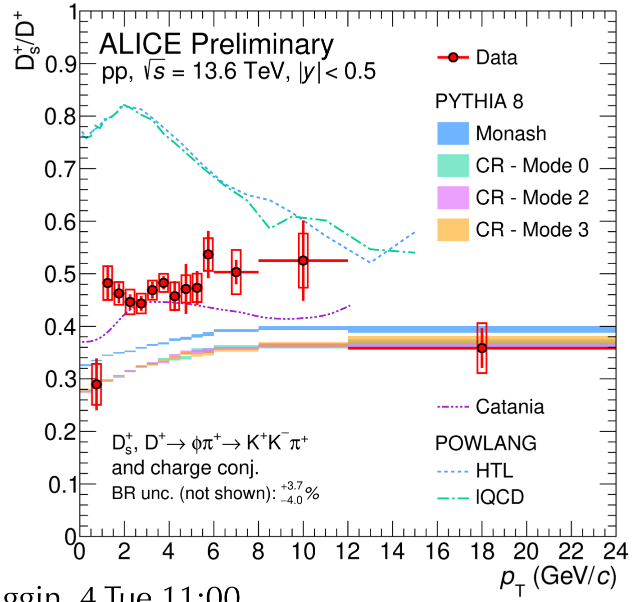
Calculation in a Box



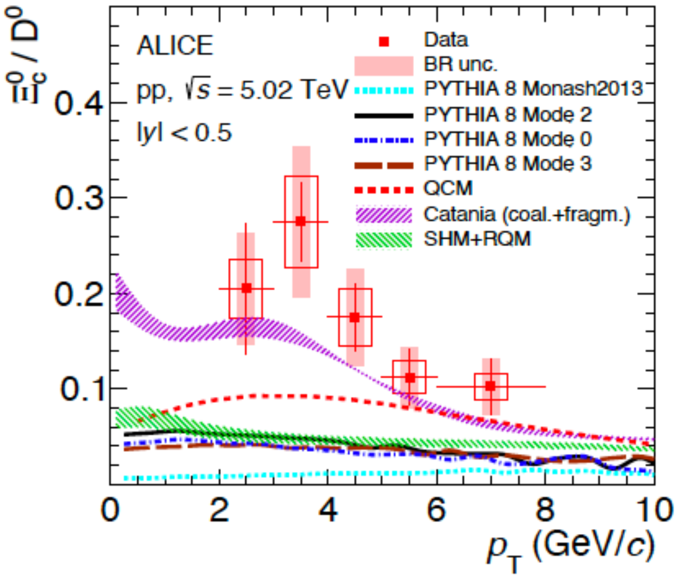
In bottom case Langevin approximation ≈ Boltzmann

But Larger M_b/T (≈ 10) the better Langevin approximation works

Strangeness in pp for HF sector

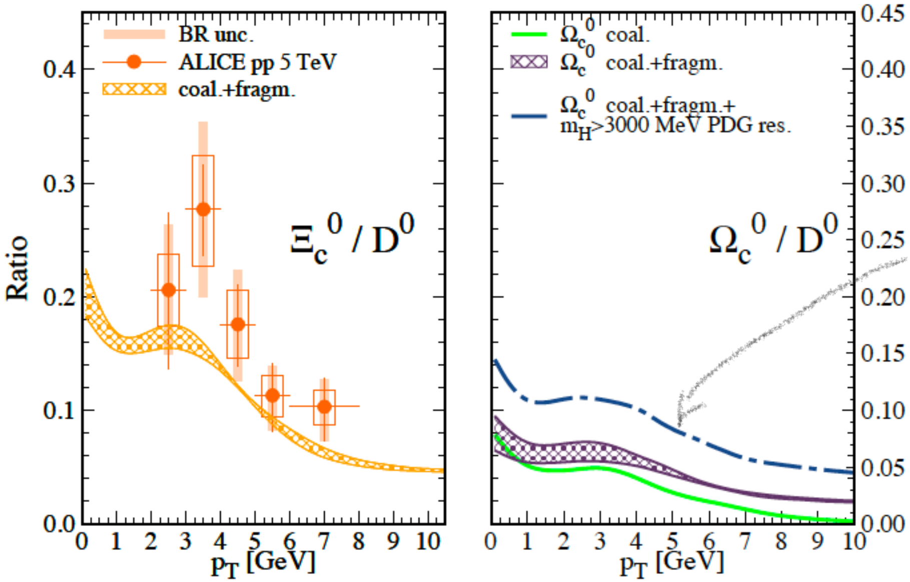


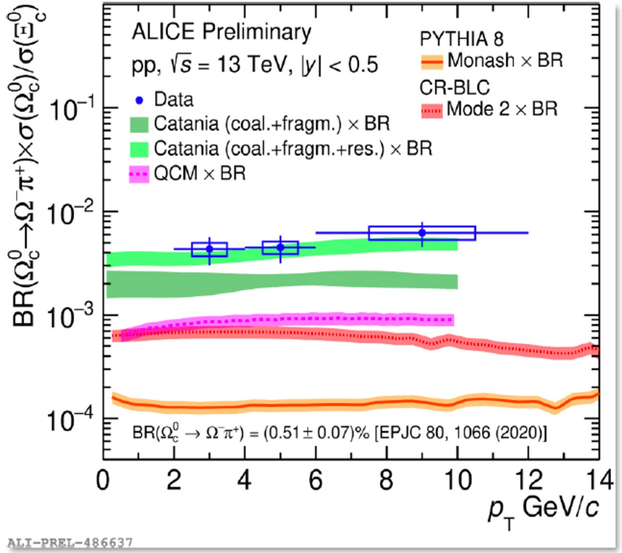
ALICE - Faggin, 4 Tue 11:00



- Catania Coalesc.+Frag. quite ok, but it is large the fragmentation contribution
- POWLANG/LCN too high, but the approach has only recombination also for mesons
- PYTHIA-CR seems to have a lack of strangeness [see also Ξ_c]

Coalescence in pp@5 ATeV





V. Minissale, Plumari, VG, PLB 821 (2021)

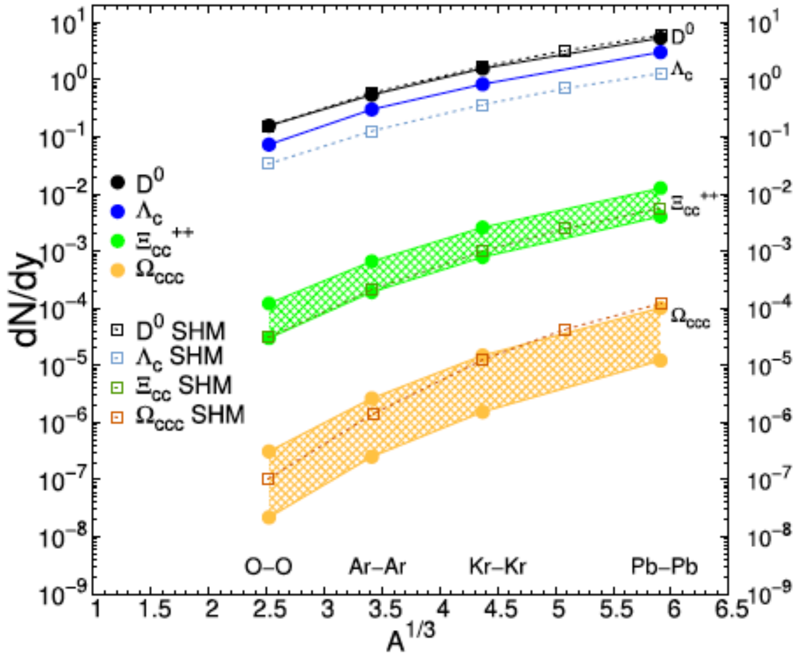
Large uncertainty in the exisiting Ω_c resonances

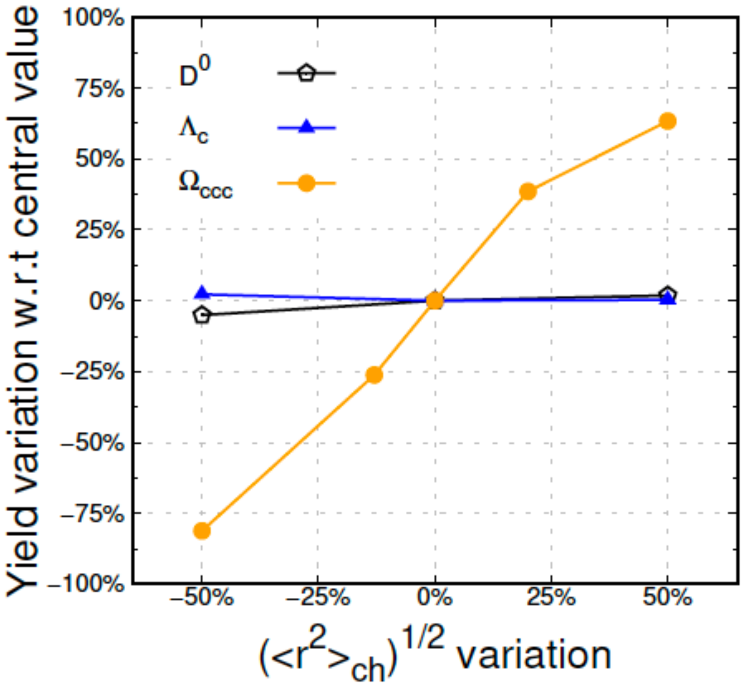
Seems to work from pp to PbPb → multi-charm production from pp to PbPb

Error band correspond to <r²> uncertainty in quark model

Evolution of Yields with system size

Minissale et al., EPJC84(2024)





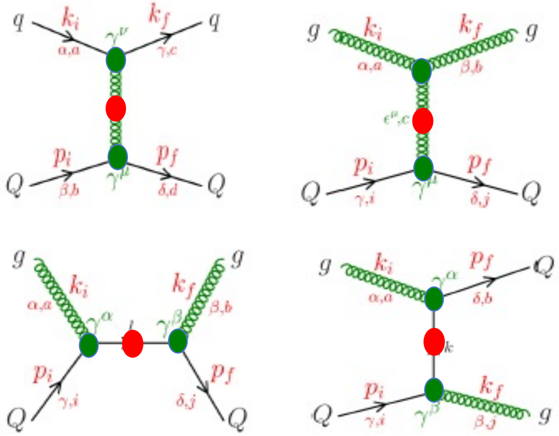
- ➢ D, Λ_c yields constrained by charm # conseervation because they dominate the yield
- ➢ Instead Ω_{ccc} is also very sensitive to wave function - <r²>

How HQ interact with the medium [low-medium p_T]

❖ **3 kinds of approaches:**

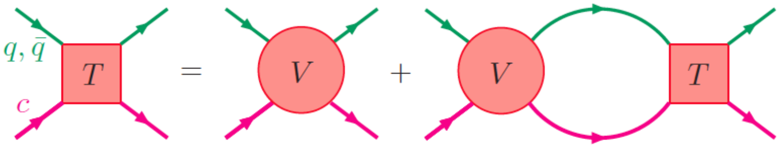
a) **pQCD inspired + HTL**
[*Nantes(+rad.) …Torino, LBL-Duke*]
LO diagrams, propagator with reduced IR regulator
$\left(q^2 - \kappa m_d^2(T)\right)^{-1}$ match **soft scale** resummed in **HTL**

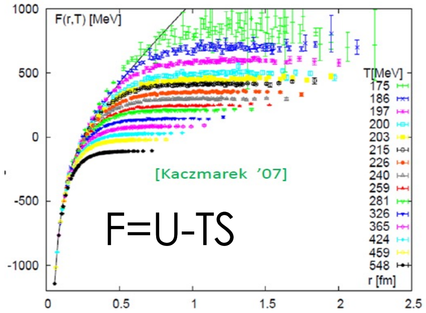
Tree-level with vertex g(T)
& propagators renormalized



b) **Quasi Particle Model + tree level diagrams**
[*Catania, Frankfurt-PHSD, QLBT o CoLBT,…*]
g(T) from a fit to lQCD-EoS
screened propagators with m_D ~ gT

c) **T-matrix:** scattering under V(r,T) deduced from lQCD (*TAMU*)





HQ momentum diffusion: lattice-QCD

From the non-relativistic limit of the Langevin equation one gets

$$\frac{dp^i}{dt} = -\eta_D p^i + \xi^i(t), \quad \text{with} \quad \langle \xi^i(t)\xi^j(t')\rangle = \delta^{ij}\delta(t-t')\kappa$$

$$\text{hence} \quad \kappa = \frac{1}{3}\int_{-\infty}^{+\infty} dt \langle \xi^i(t)\xi^i(0)\rangle_{\rm HQ} = \frac{1}{3}\int_{-\infty}^{+\infty} dt \underbrace{\langle F^i(t)F^i(0)\rangle_{\rm HQ}}_{\equiv D^>(t)}$$

Lattice-QCD simulations provide *Euclidean* $(t=-i\tau)$ electric-field $(M=\infty)$ correlator

$$D_E(\tau) = -\frac{\langle {\rm Re\,Tr}[U(\beta,\tau)gE^i(\tau,\mathbf{0})U(\tau,0)gE^i(0,\mathbf{0})]\rangle}{\langle {\rm Re\,Tr}[U(\beta,0)]\rangle}$$

How to proceed? κ comes from the $\omega \to 0$ limit of the FT of $D^>$. In a thermal ensemble $\sigma(\omega) \equiv D^>(\omega) - D^<(\omega) = (1-e^{-\beta\omega})D^>(\omega)$, so that

$$\kappa \equiv \lim_{\omega\to 0}\frac{D^>(\omega)}{3} = \lim_{\omega\to 0}\frac{1}{3}\frac{\sigma(\omega)}{1-e^{-\beta\omega}} \underset{\omega\to 0}{\sim} \frac{1}{3}\frac{T}{\omega}\sigma(\omega)$$

From $D_E(\tau)$ one extracts the spectral density according to

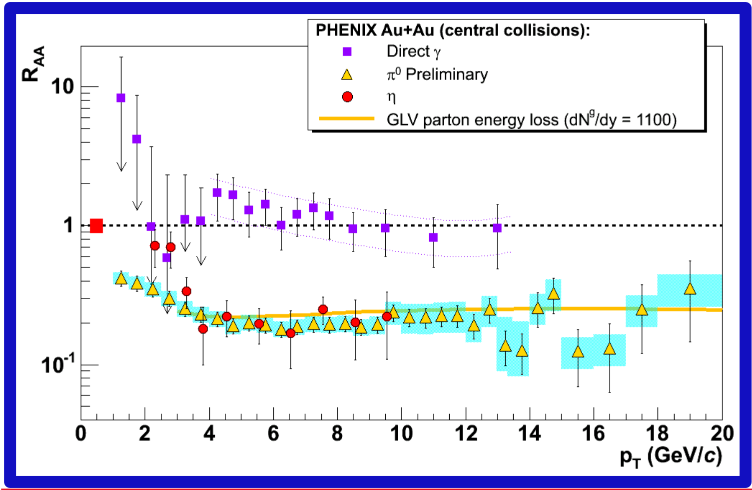
$$D_E(\tau) = \int_0^{+\infty}\frac{d\omega}{2\pi}\frac{\cosh(\tau-\beta/2)}{\sinh(\beta\omega/2)}\sigma(\omega)$$

Two Main Observables in HIC

❖ Nuclear Modification factor

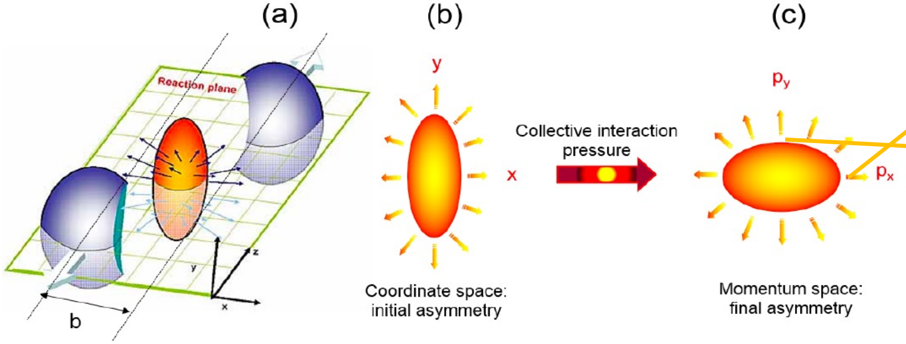
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{N_{coll} d^2N^{NN}/dp_T d\eta}$$

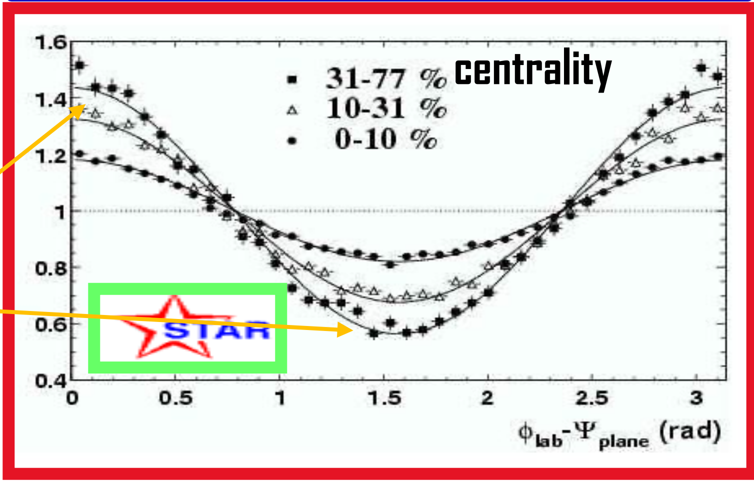
- Modification respect to pp
- Decrease with increasing partonic interaction



❖ Anisotropy p-space: Elliptic Flow v_2

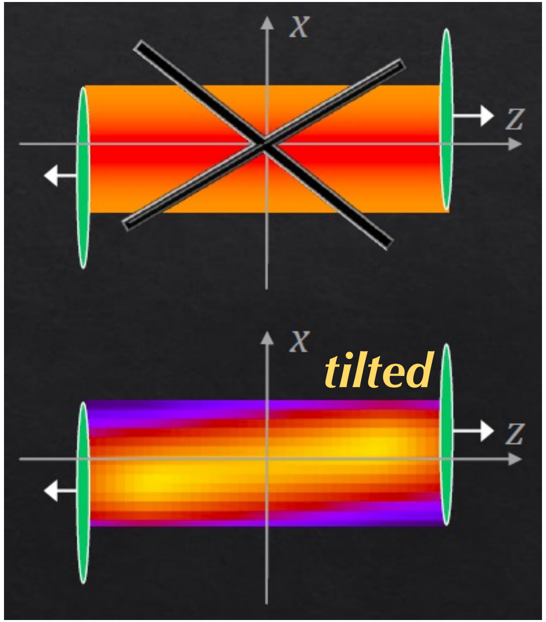
$$\frac{dN}{p_T dp_T d\varphi} = \frac{dN}{2\pi p_T dp_T}[1 + 2v_2\cos(2\varphi) + ...]$$

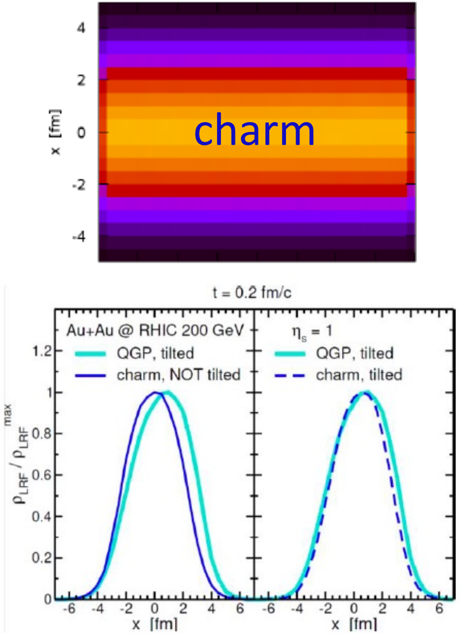




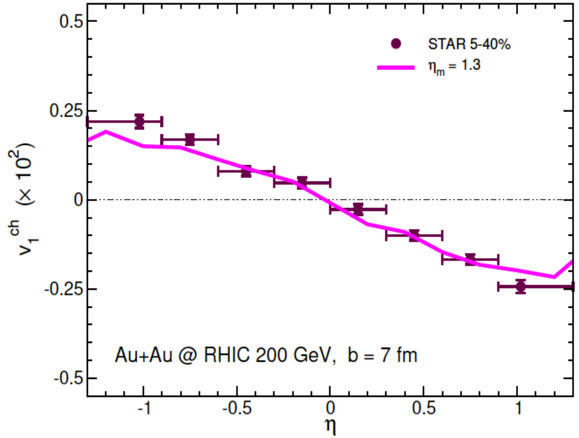
v_1 of D mesons: quantitative study

Oliva, Plumari, V.G., JHEP(2020)





"Tilt" fix bulk v_1



$$W(x_\perp, \eta_s) = 2\left(N_A(x_\perp) f_-(\eta_s) + N_B(x_\perp) f_+(\eta_s)\right)$$

$$f_+(\eta_s) = f_-(-\eta_s) = \begin{cases} 0 & \eta_s < -\eta_m \\ \dfrac{\eta_s + \eta_m}{2\eta_m} & -\eta_m \leq \eta_s \leq \eta_m \\ 1 & \eta_s > \eta_m \end{cases}$$