Heavy Flavor Dynamics in Hot QCD matter

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NextGenerationEU

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

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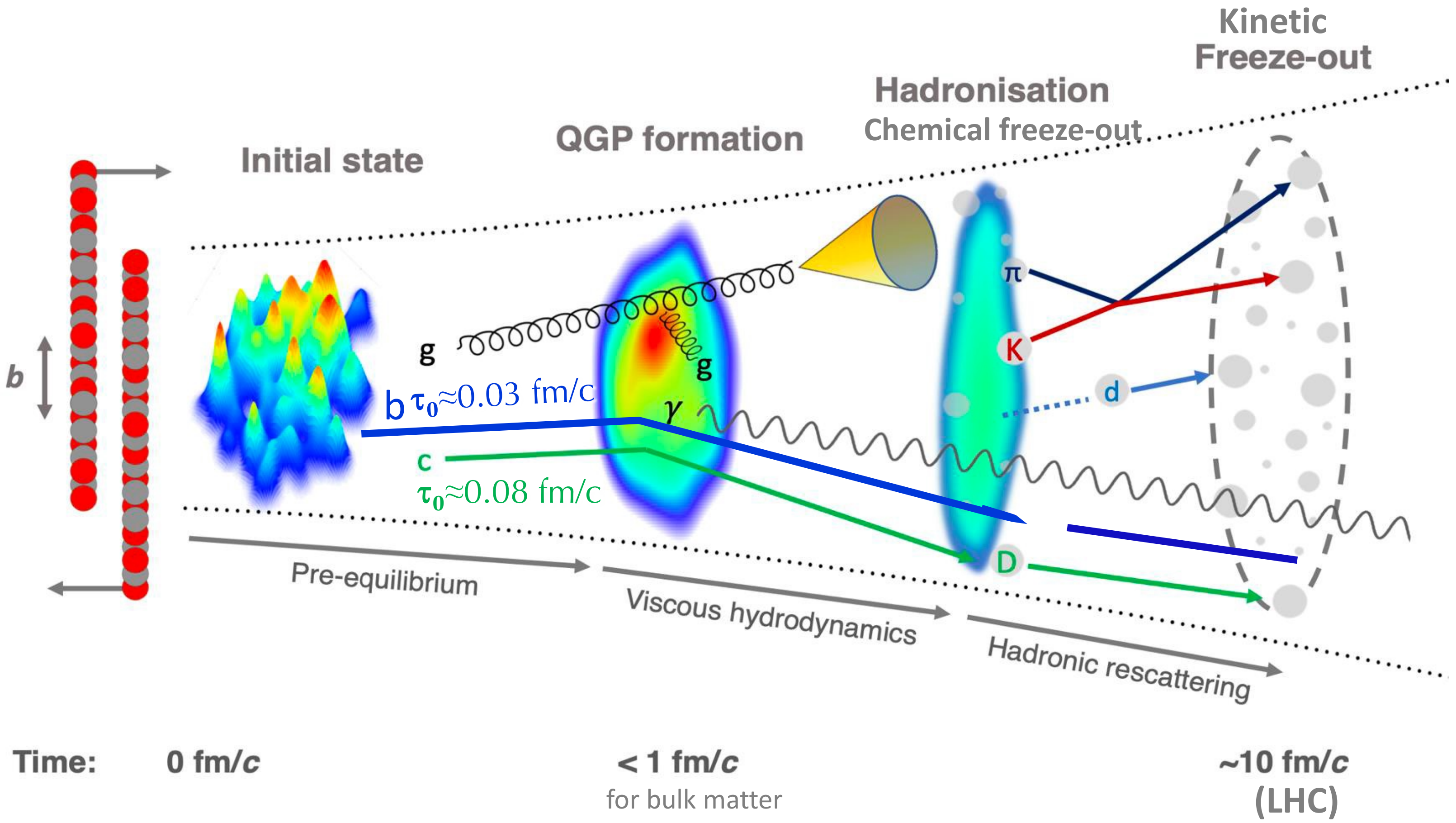
Sketch of Time evolution of uRHICs

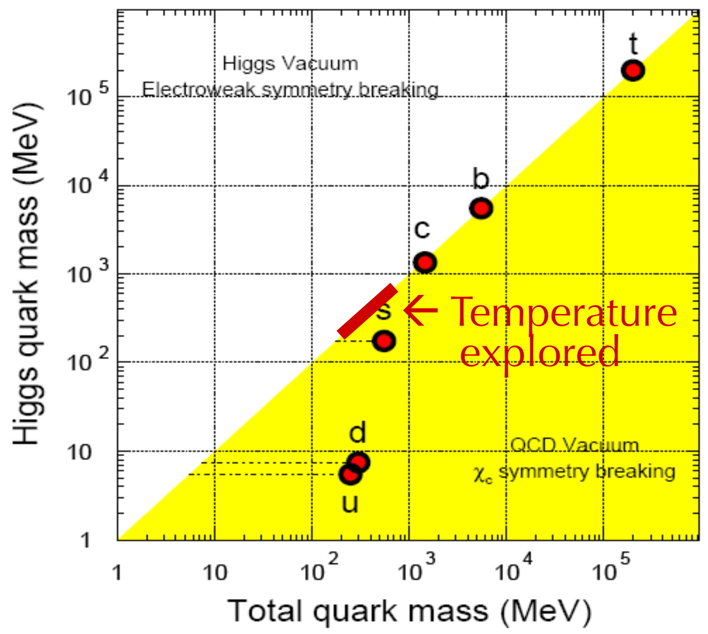


Adapted from ALICE

Outline

- ✧ **Basic concepts & motivation for HQ physics in uRHICs**
- ✧ **Results from the first & second stage:**
  - strong non-perturbative HQ dynamics [agreement to LQCD?!, close to AdS/CFT limit?]
  - non-universal hadronizationin AA≠ e^+e^- seems so already for pp@TeV
- ✧ **Next steps:** low p_T, extension to b & access to new observables
- ✧ **HQ as probe of Glasma early stage phase**

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:

- $\tau_0 \approx \mathbf{1/2m_Q}$ (<0.1 fm/c)<< τ_{QGP} witness of all QGP evolution
- $\tau_{th} \approx \tau_{QGP} >> \tau_{q,g}$ carry more information of their evolution

Reviews:
- F. Prino and R. Rapp, JPG (2019)
- X. Dong and VG, Prog.Part.Nucl.Phys. (2019)
- Jiaxing Zhao et al., Prog.Part.Nucl.Phys. (2020)

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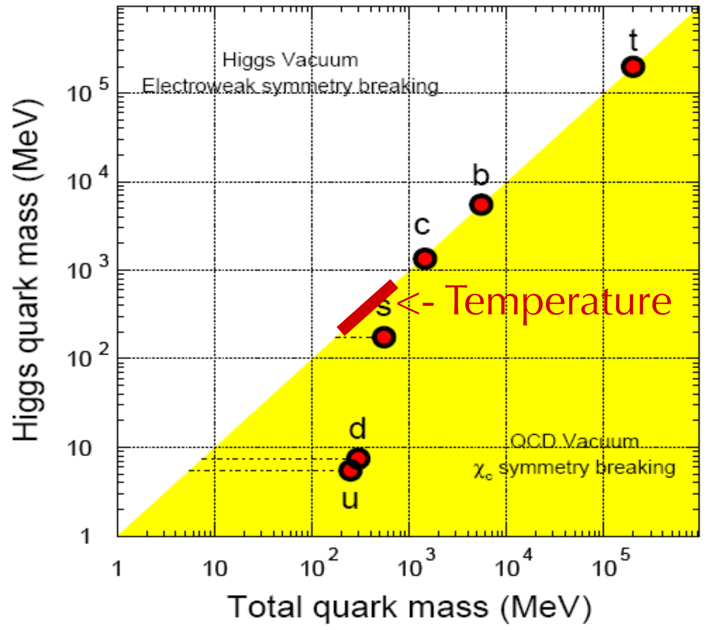

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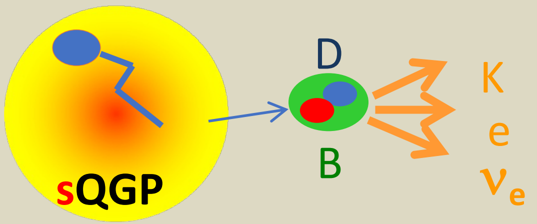
* For HQ we know initial p_T distribution at variance with light quark & gluons

* HQ not created at hadronization by string breaking + const. quarks close to energy conservation

Standard Dynamics of Heavy Quarks in the QGP

c,b quarks



Brownian Motion limit

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

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

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

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

$D_p = ET\gamma$ – 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…

Space diffusion coefficient $D_s = \frac{T}{M\gamma} = \frac{T^2}{D_p} = \frac{T}{M}\tau_{th}$

- ✧ This is the main set up at least at $p_T < 6$-8 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

HQ link to Lattice QCD at finite T

❖ Ab-initio Diffusion Transport Coefficient

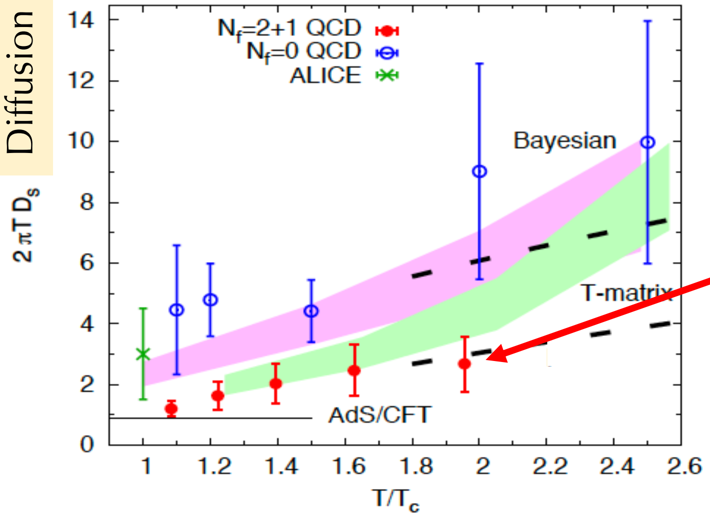
Spectral function ρ_E extracted **from euclidean color-electric correlator** $D_E(\tau)$ →

Kubo formula diffusion in the p→0 limit:

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

L. Altenkort et al., PRL131 (2024)

Diffusion



Approximations/limitations:

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

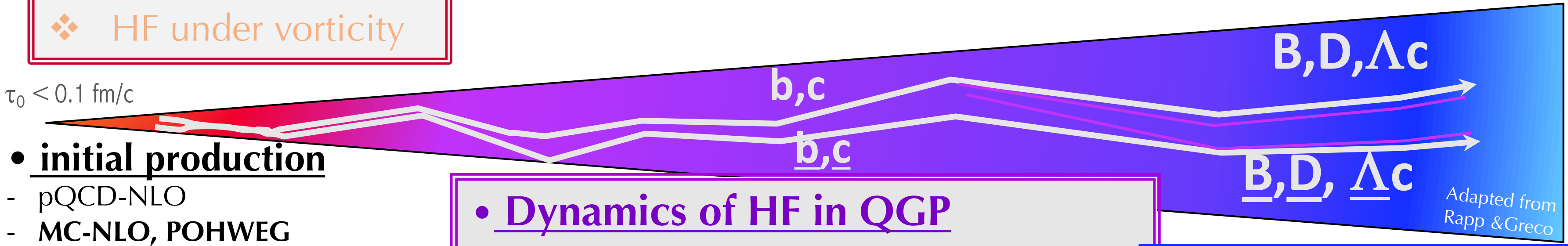
HQ allow for developing a NRQCD EFT at finite T & many-body T-matrix from V(r,T) by LQCD

Studying the HF in uRHIC

0 0.5 5 10

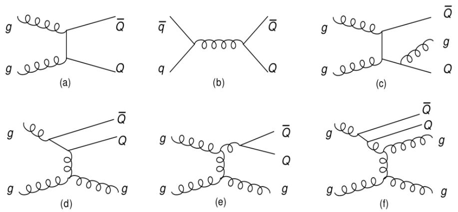
τ [fm/c]

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



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

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



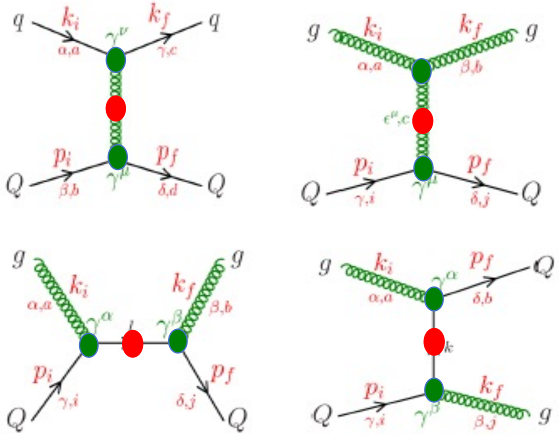
- **Dynamics of HF in QGP**
  - **Themalization**
  - **Transp. Coeff. of QCD matter $D_s(T)$**
  - Radiative E_{loss} & Jet Quenching

- **Hadronization**
  - coalescence and/or fragm.
  - large Λ_c/D in pp,pA,AA
  - → affects observables

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

❖ **3 kinds of approaches:**

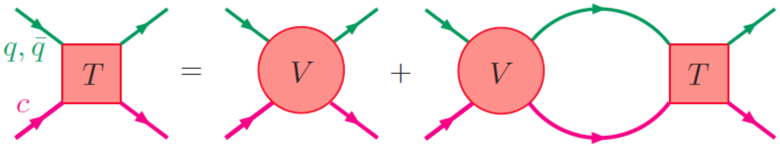
Tree-level with vertex g(T)
& propagators renormalized

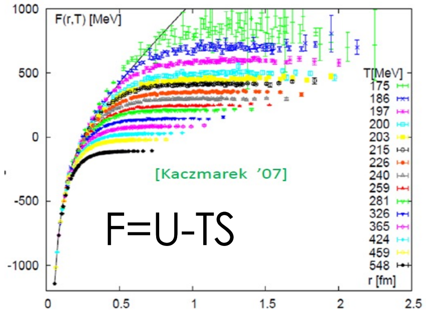


a) **pQCD inspired + HTL**
[*Nantes(+rad.) …Torino, LBL-Duke*]
LO diagrams, propagator with reduced IR regulator
$\left(q^2 - \kappa m_d^2(T)\right)^{-1}$ match **soft scale** resummed in **HTL**

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*)



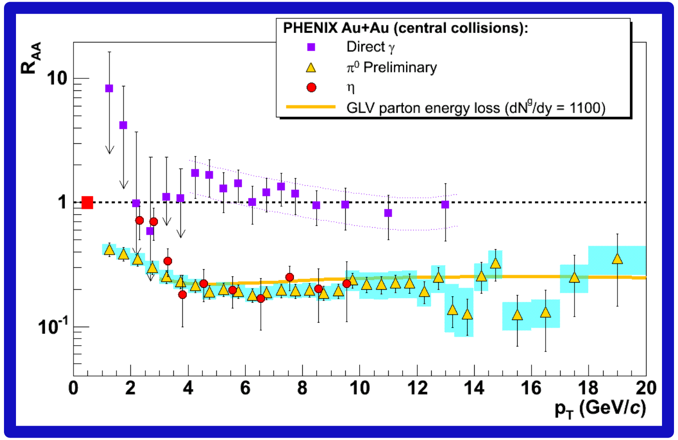


Two Main Observables in HIC

❖ Nuclear Modification factor

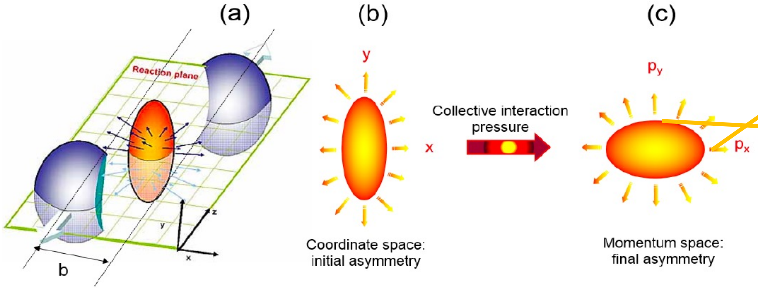
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{N_{coll} d^2N^{NN}/dp_T d\eta}$$

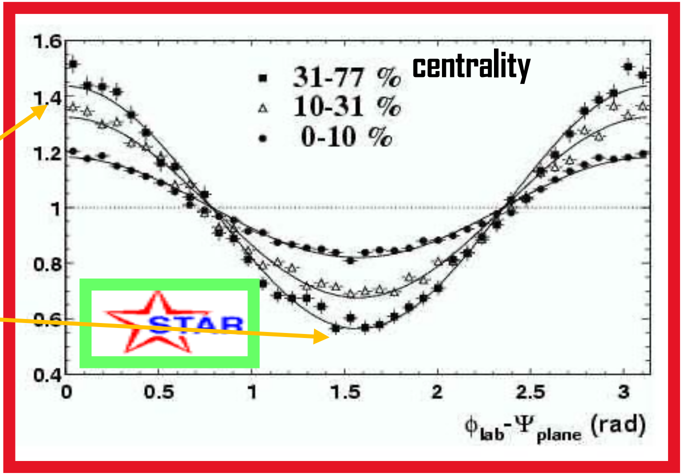
- Modification respect to pp
- Decrease with increasing partonic interaction



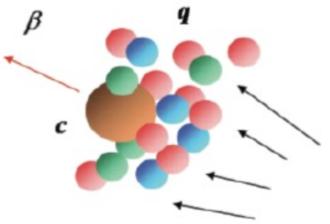
❖ Anisotropy p-space: Elliptic Flow v_2

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





What was the expectation for charm?

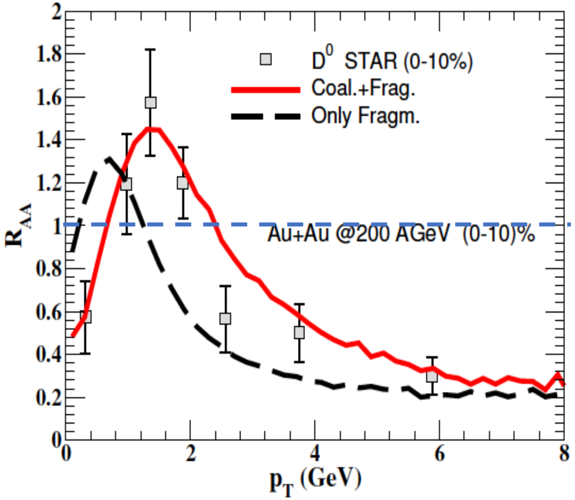


QGP created is made by 99% of q=u,d,s, + Charm Quarks <1%

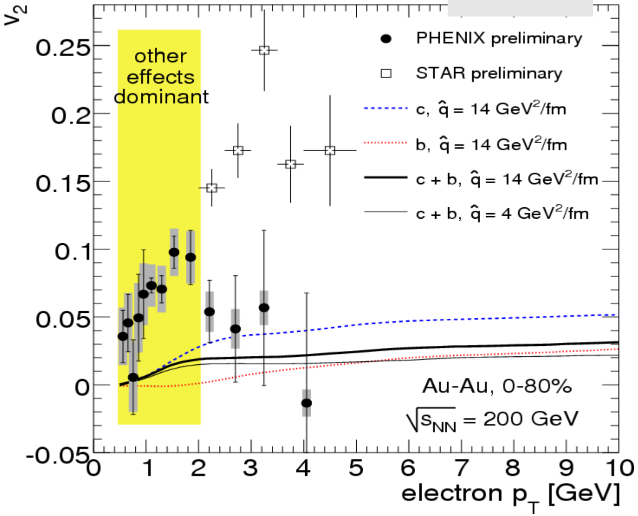
$m_q \approx$ 0.01 GeV & $M_c \approx$ 1,3 GeV → poorly dragged & long thermalization time :

In LO-pQCD $\tau_{C,therm} \approx$ 20 fm/c >> τ_{QGP} >> $\tau_{q,therm} \approx$ O(1) fm/c → **R_{AA} ~1 and v_2 ~0**

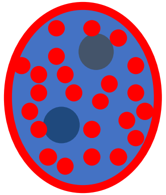
For plasma conditions realistically obtainable in the nuclear collisions (T~250 MeV, g=2) → *effective masses $m_{q,g}$* ~ gT~500 MeV"*



~2005



R_{AA} & v_2 with upscaled pQCD cross section



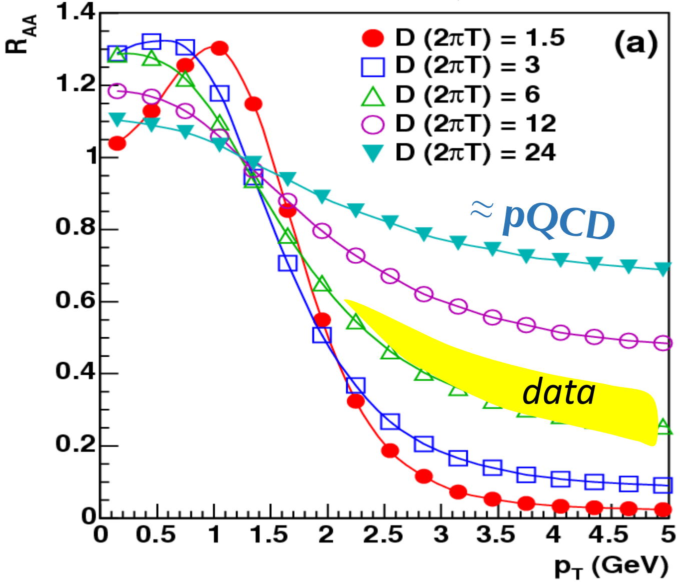
Fokker-Plank for charm interaction in a hydro bulk

Diffusion coefficient

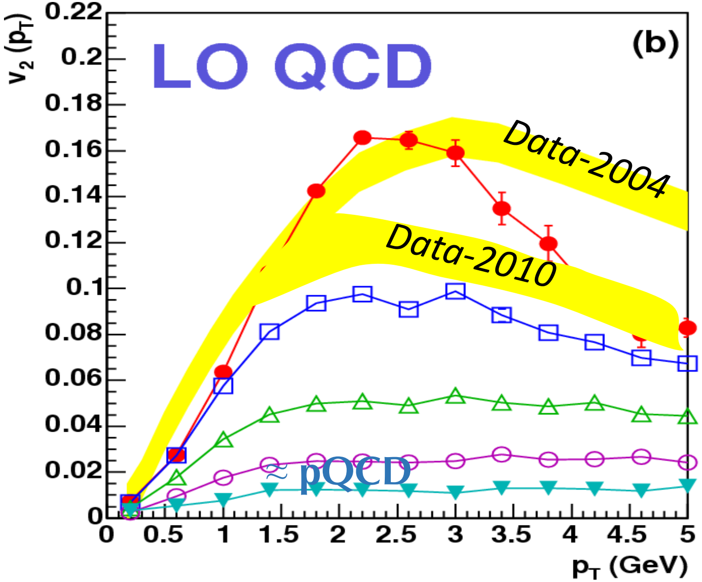
$$D_p \propto \int d^3k \left| M_{g(q)c \to g(q)c}(k,p) \right|^2 k^2$$

scattering matrix

Moore & Teaney, PRC71 (2005)



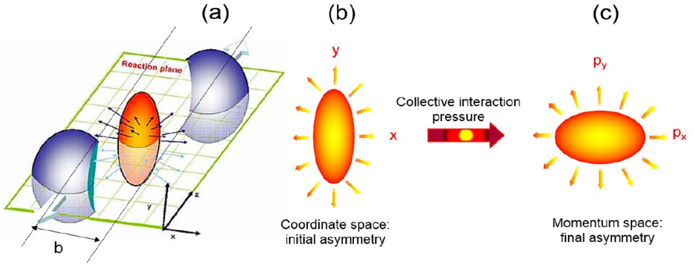
Multiplying by a K-factor pQCD



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

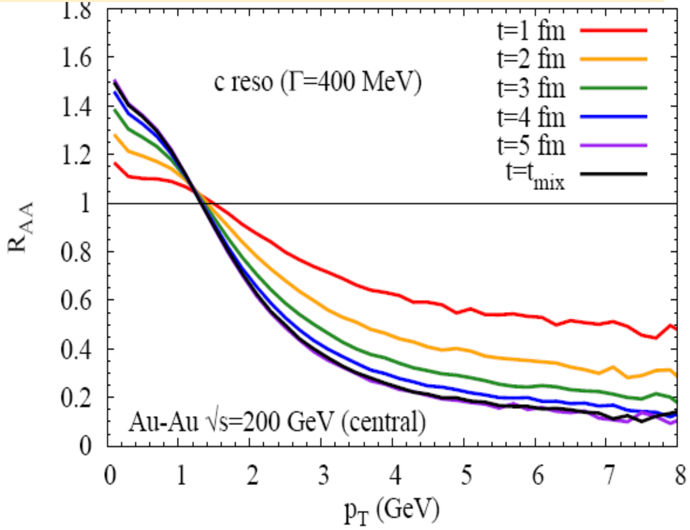
R_{AA} and v_2 evolution & correlation

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

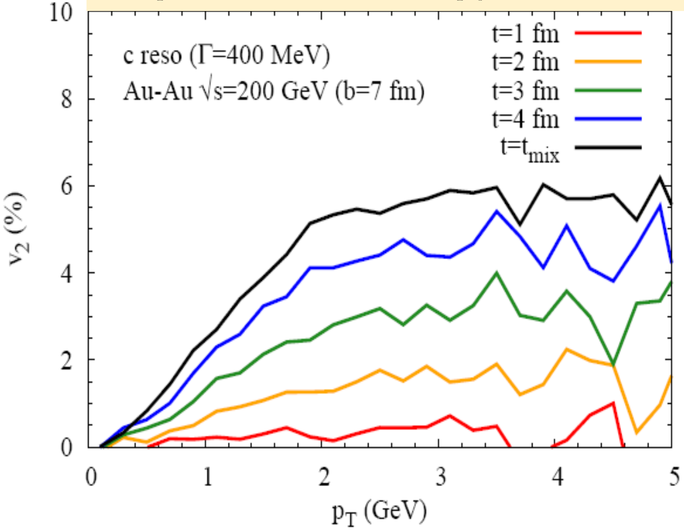


R_{AA} is "generated" faster than v_2

R_{AA} Ratio normalized p_T spectra pp/AA



Elliptic Flow:Anisotropy Azimuthal emission

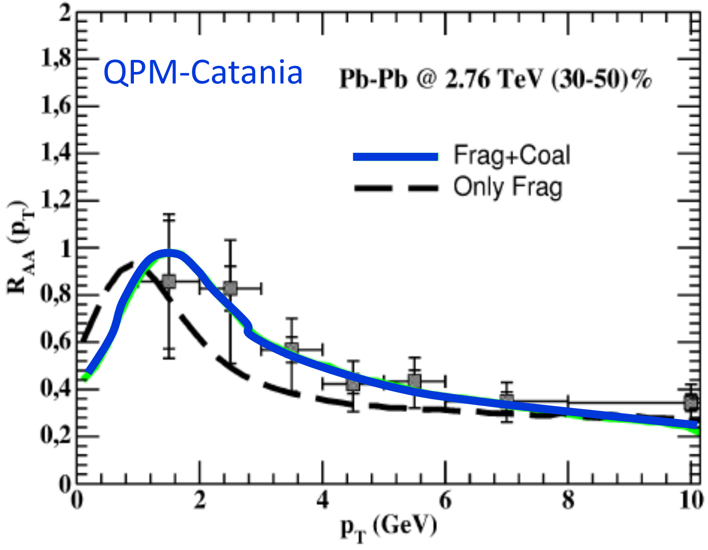


v_2 formation time t~ R
+
for HQ come from
The drag of QGP fluid

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

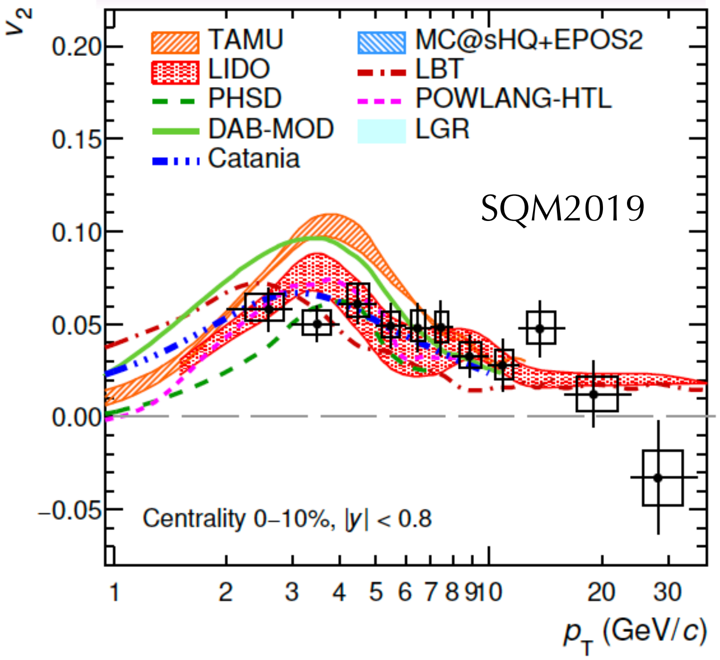
Studying charm in uRHICs – after Run 2

R_{AA}



Scardina et al., PRC96(2017)

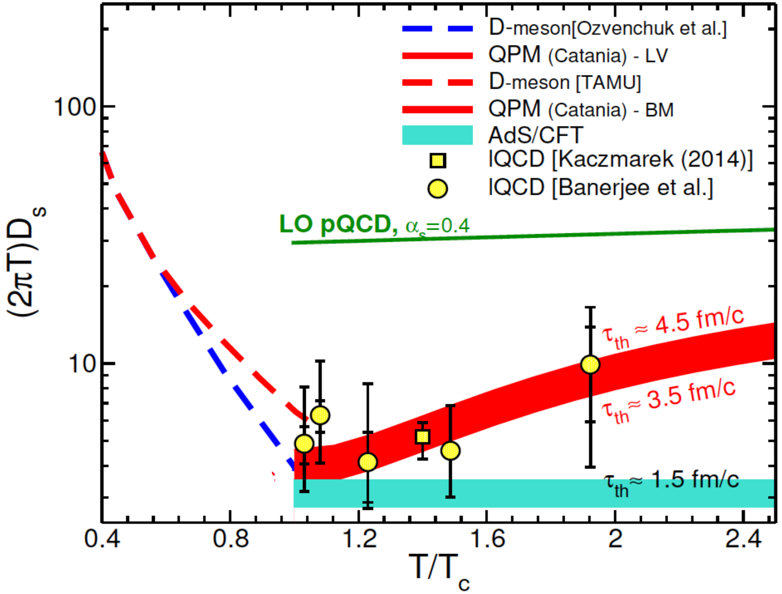
v_2



Note: early data $p_T > 1.5$-2 GeV with significant error bars

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)

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

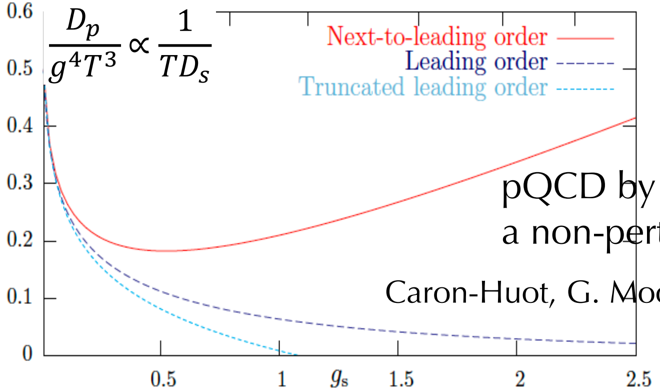
pQCD, Asymptotic free regime

Not a model fit to lQCD data!

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

Infinite Strong Coupling (AdS/CFT)

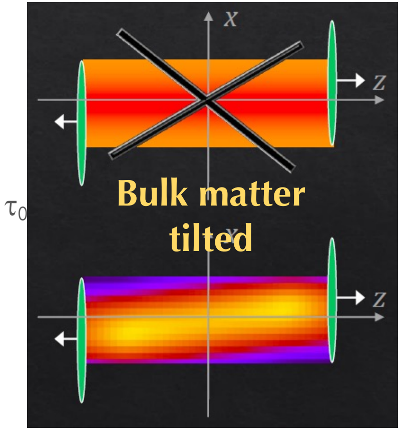
- Largely non-perturbative D_s (close AdS/CFT) even if $M_Q >> \Lambda_{QCD}$, m_q (bare) τ_{th}(charm, p→0) < 5 fm/c

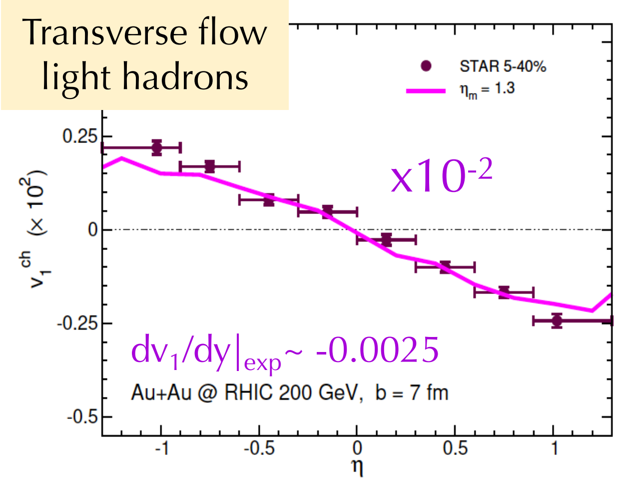


pQCD by itself indicates a non-pert. behavior

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

HQ Surprise also in the transverse flow $v_1 = <p_x/p_T>$





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,..)

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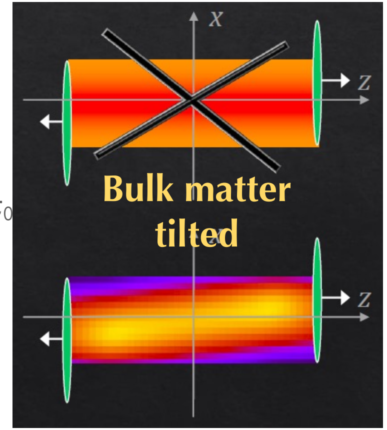

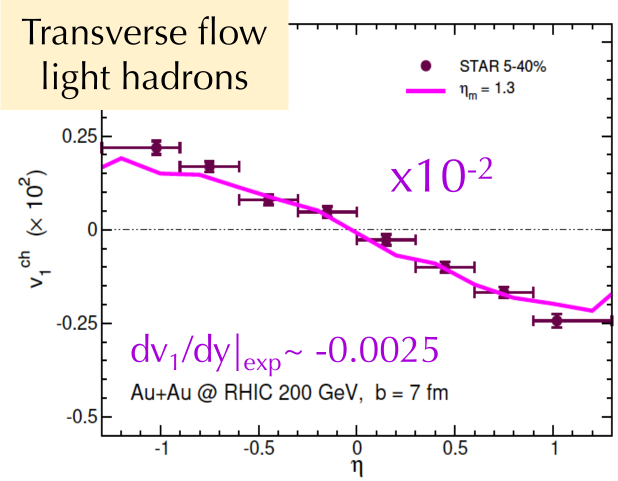

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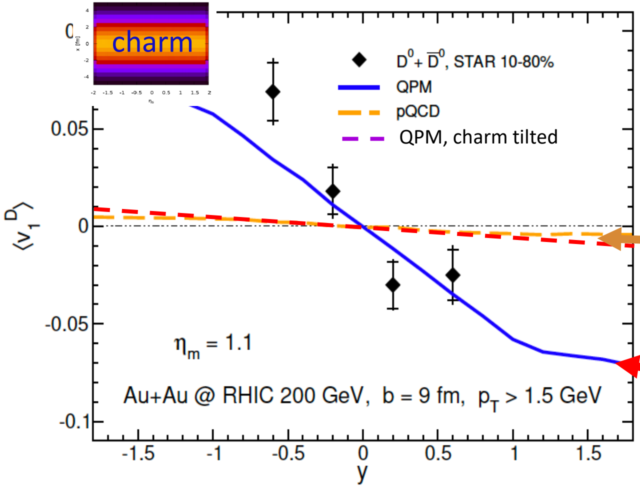
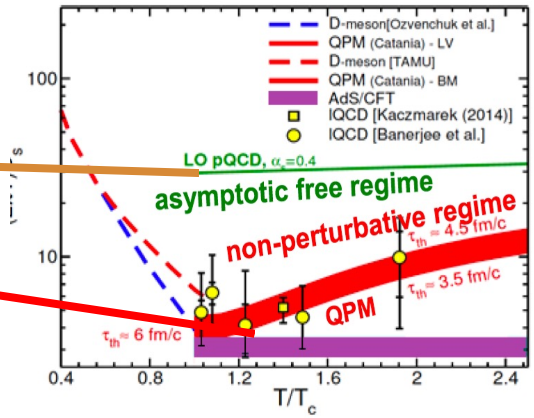
$dv_1/dy = -0.080 \pm 0.017(\text{stat}) \pm 0.016(\text{syst})$



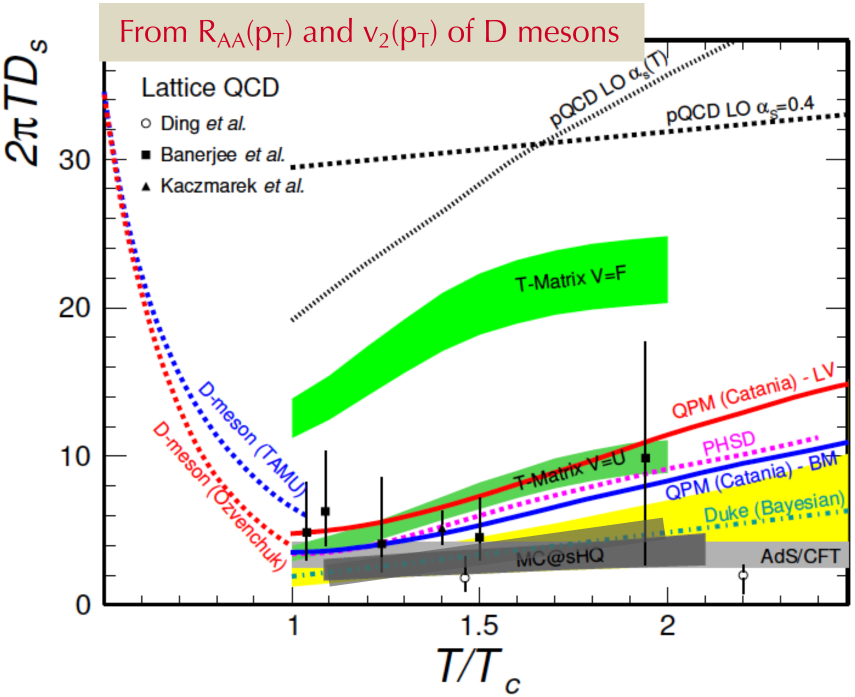


- ❖ **Needed non-perturbative HQ interaction close to AdS/CFT**
- ❖ Needed also initial "tilt" of bulk & none for HQ

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

Diffusion of Charm Quark: first stage

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



$$\tau_{th} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8 \frac{2\pi T D_s}{(T/T_c)^2} \text{ fm/c} \approx \mathbf{2.5\text{-}6 \text{ fm/c}} \ (p \rightarrow 0, T_c)$$

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

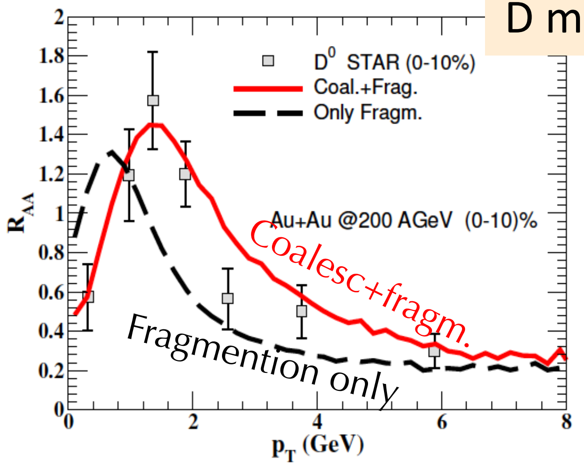
- quenched QCD (Yang-Mills) + $M_Q \rightarrow \infty$
- **phenomenology at intermediate p_T – LQCD(AdS/CFT) at $p \rightarrow 0$**

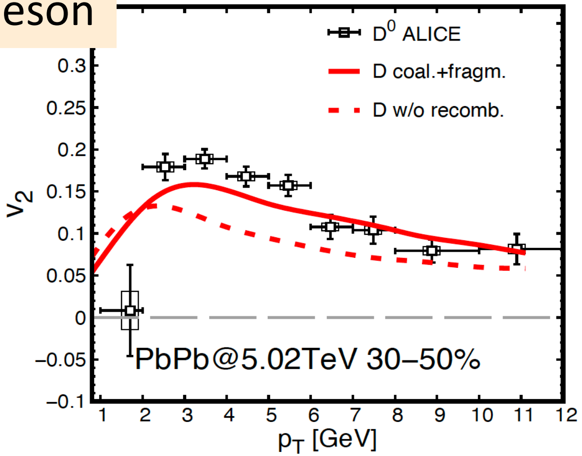
*Main sources of differences in models:

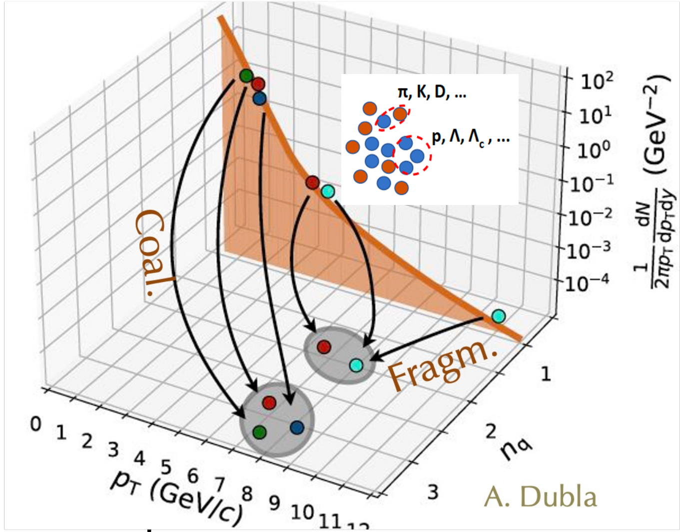
- impact of **hadronization** («unexpected» large baryon production)
- **momentum depedence of matrix elements**
- **data not enough precise/observable not enough constraining (especially for $p_T \rightarrow 0$)**

Impact of HF in-medium Hadronization

D meson







- Opposite to in-medium scattering Coalescence **brings up both** R_{AA} and v_2
  → toward experimental data

Phase-space coalescence: quark recombination

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

Independent Fragmentation

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

→Add momenta: P_T^H from low p_T quark

→ Enhance elliptic flow v_2 adding flows:

$$v_{2D}(p_T) \cong v_{2c}\left(\frac{m_c}{m_D} p_T\right) + v_{2q}\left(\frac{m_q}{m_D} p_T\right)$$

HF Baryon enhancement wrt e^+e^- even in AA& pp@TeV

Phase-space coalescence

Parton Distrib. Funct. — Hadron Wigner function

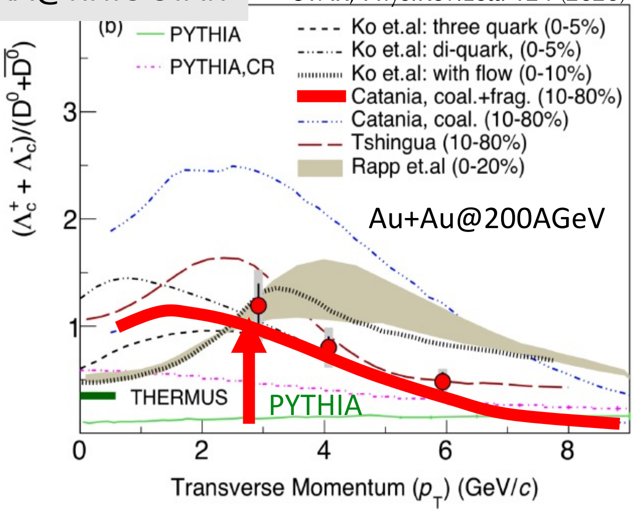
$$\frac{dN_{Hadron}}{d^2p_T} = g_H \int \prod_{i=1}^{n} p_i \cdot d\sigma_i \frac{d^3 p_i}{(2\pi)^3} f_q(x_i, p_i)\, f_W(x_1, \ldots, x_n; p_1, \ldots, p_n)\, \delta\left(p_T - \sum_i p_{iT}\right)$$

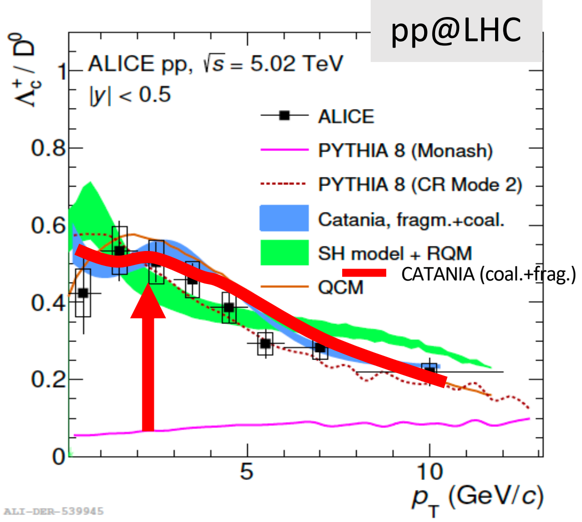
Fragmentation

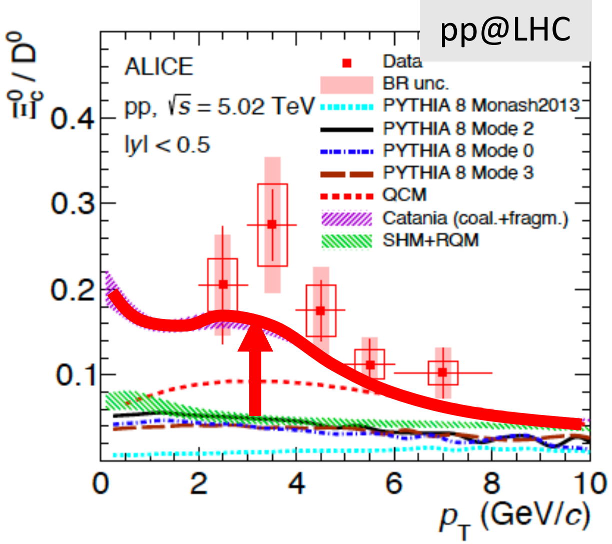
$$\frac{dN_h}{d^2p_h} = \sum_f \int dz \frac{dN_f}{d^2p_f} D_{f\to h}(z)$$

AA@RHIC-STAR

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



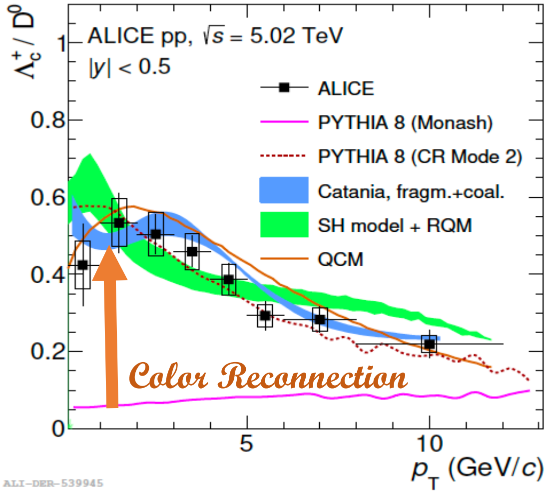


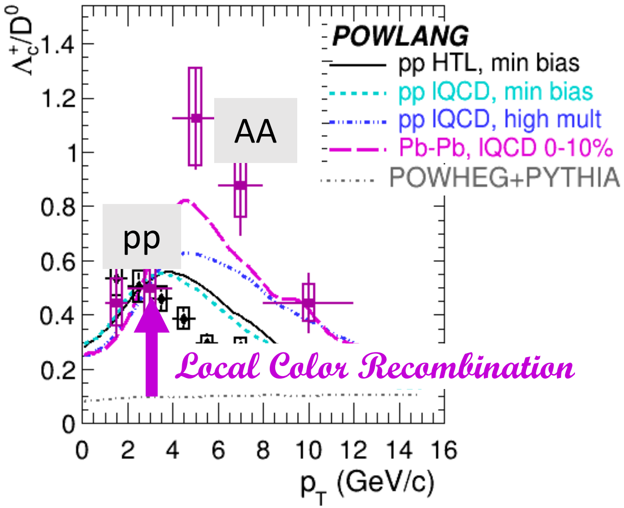


- I^0 prediction in coalescence [Ko PRC(2009)] of very large Λ_c/D^0 >> SHM[PDG] >> e^+e^-(~PYTHIA)
- Breaking of Universal Fragmentation Function already in pp in HF sector

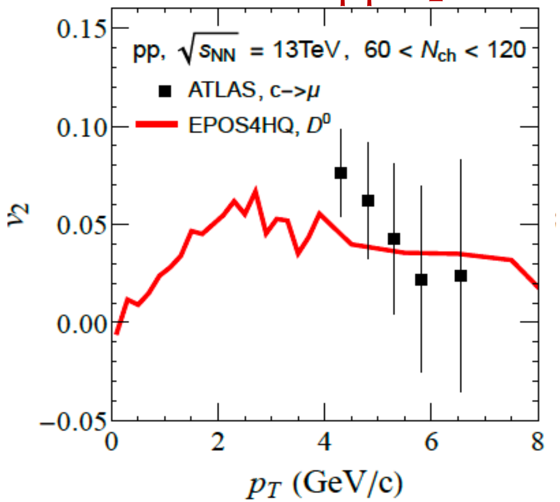
HF hadronization has stimulated several developments

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



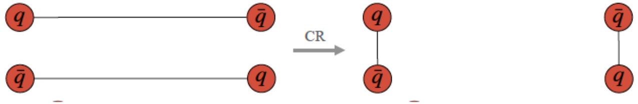


even in pp v_2

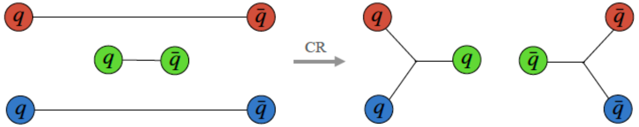


- Yields modified from e^+e^- (e^-p) to pp, then from pp to AA mostly coupling to flowing QGP medium modifies p_T shape of the ratio Λc/D?

PYTHIA Color Reconnection/ Local Color neutralization



(a) Dipole-type reconnection.

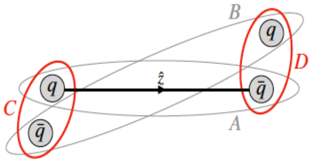


Baryonic reconnection

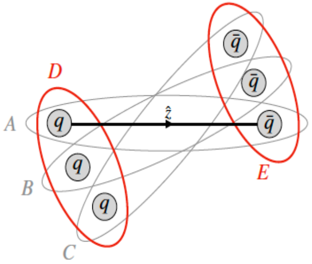
Leading Color ($N_c \rightarrow \infty$): Prob. of Local Color neutralization→0

- 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 (like in coalescence)



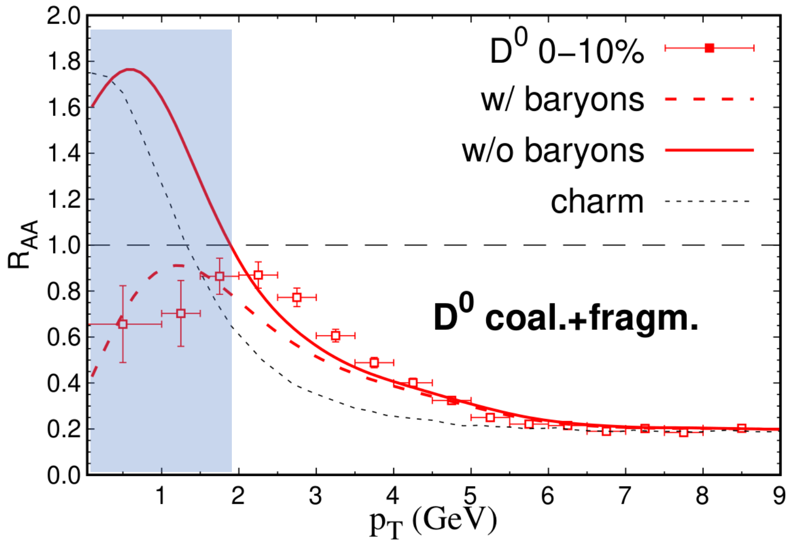
(a) Mesonic reconnection.



(b) Baryonic reconnection.

Altmann et al., *Towards the understanding of heavy quarks hadronization: from leptonic to heavy-ion collisions,* EPJC 85 (2025)

HF Baryon enhancement: impact on R_{AA}



Till 2019-20 the baryon production (Λ_c,…) was discarded by theoretical approaches

But data at p_T> 2 GeV nearly blind to it

Λ_c baryon production was mostly neglected in most studies of R_{AA}, but:

- Strong impact on R_{AA} low-intermediate p_T→affect estimates of D_s

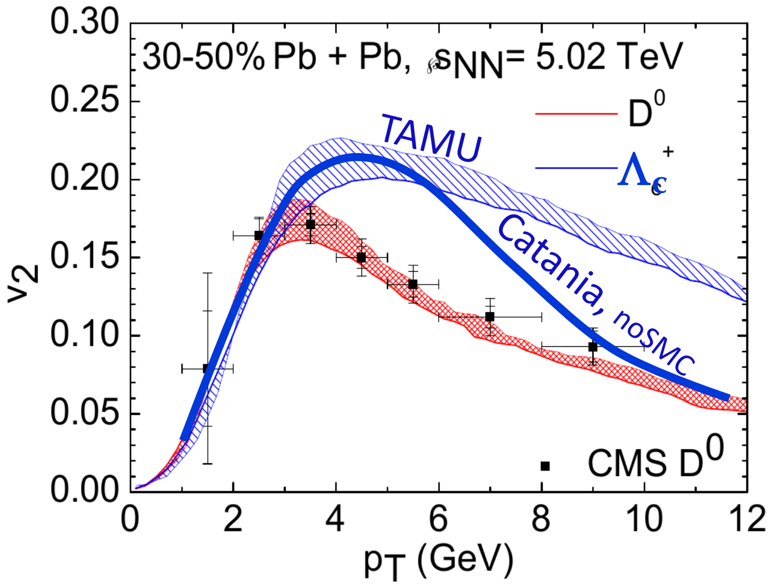
"See" Hadronization mechanism through elliptic flow

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

→ Large v_2 of $\Lambda_c \sim \; v_{2c}\left(\frac{m_c}{m_\Lambda} p_T\right) + 2\, v_{2q}\left(\frac{m_q}{m_\Lambda} p_T\right)$

→ Effect to be measured in AA; will it be seen also in pp?

[for Run3-4]



He and Rapp, PRL 2020

✓ **Λ_c dominated by coalescence:**
p_T range? self-consistent with Λ_c/D ratio?

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

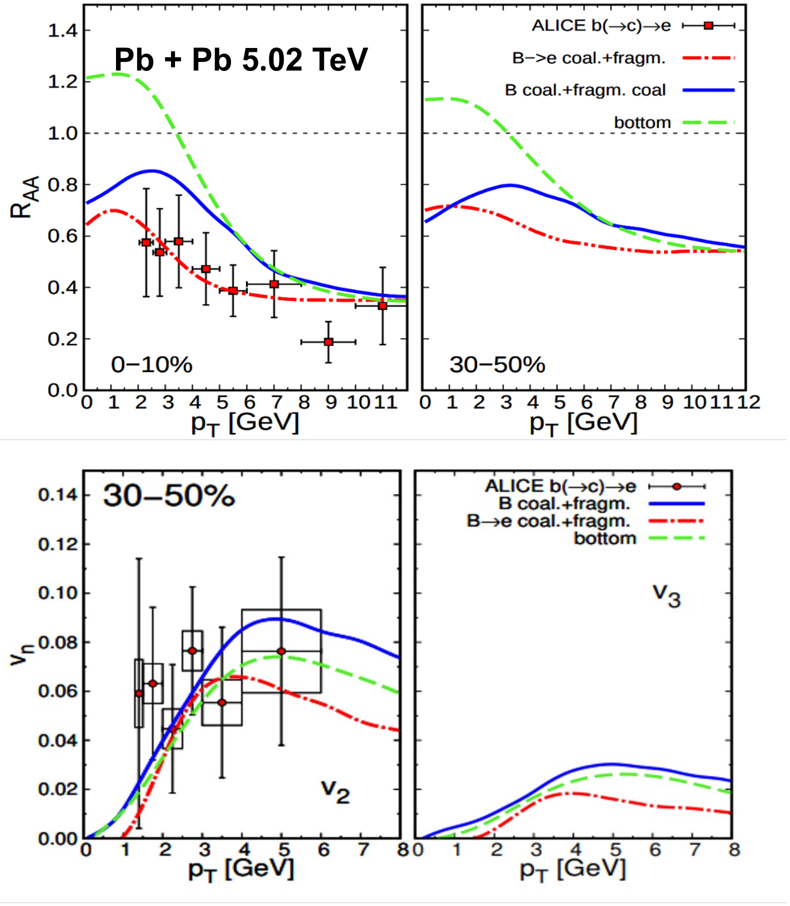
Methods/tools of AA allow better insight into hadronization in pp!?

Is charm quark really "heavy"?

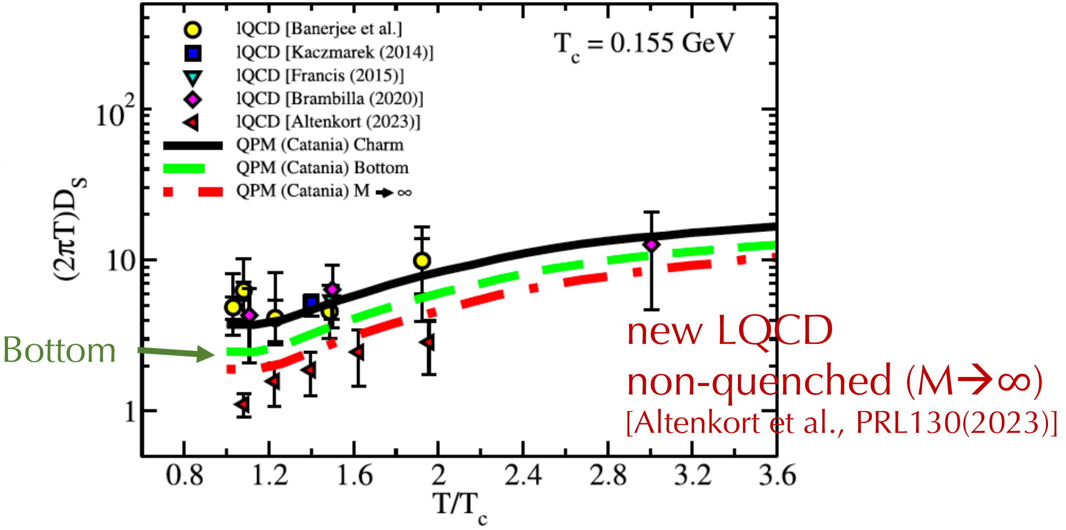
A very solid comparison to LQCD, to the development of NRQCD-EFT, to quantify interaction only by space-diffusion D_s (full Brownian motion) requires a "full" HQ , but **M_c~ q^2~ gT, <p>~3T** at T~ 300-500 MeV

→ **full Heavy is the Bottom**

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

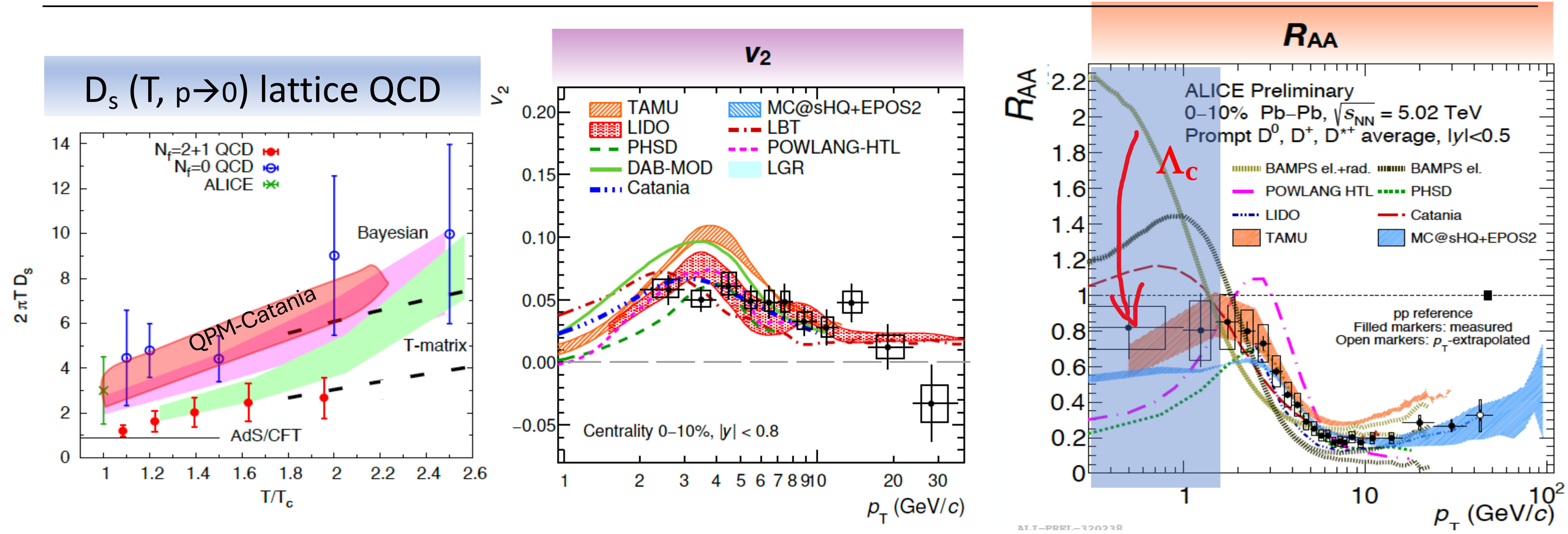


- No parameters changed wrt charm (only M_b)
- Agreement within still large uncertainty
- QPM implies a mass dependence of $D_s(T)$, not seen in LQCD/NRQCD



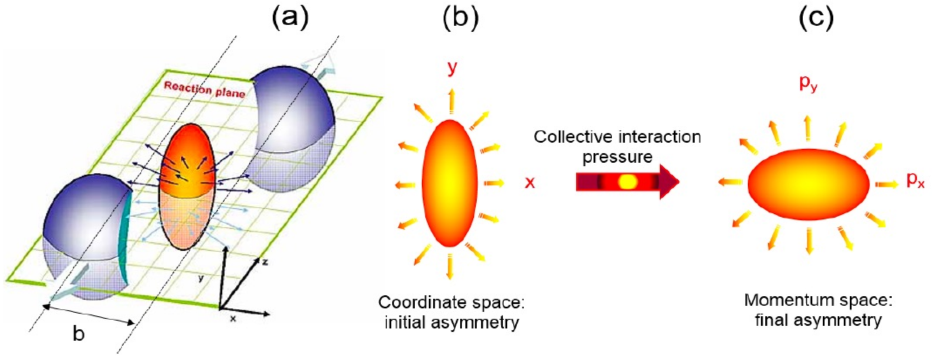
M.L. Sambataro et al., *PLB* 849(2024)

Phase of Transition

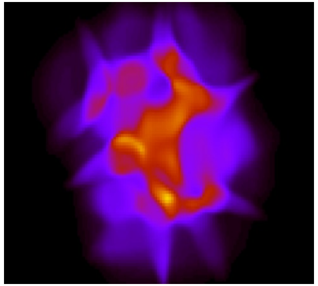


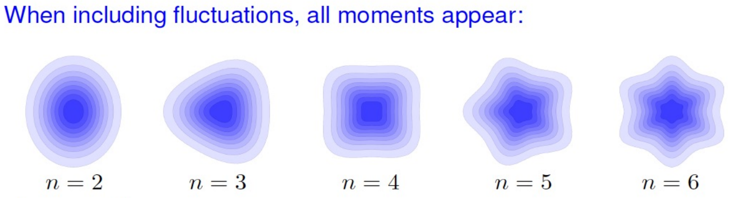
- Very small new LQCD-D_s (T) [τ_{th}(charm, p→0)~ 1-2 fm/c]: mass independent? down to charm mass?
- Most studies at p_T>1.5-2 GeV [mainly not including impact of Λ_c], need **new wave of prediction**:
  - → compare to LQCD **need data p_T→ 0**
  - → need precision data at low p_T not only for D but also for Λ_c
  - → add more esclusive observables: v_n(soft)-v_n(hard), angular $D\bar{D}$ correlation,…

Going deeply into Hot QCD matter created in uRHICs



event-by-event

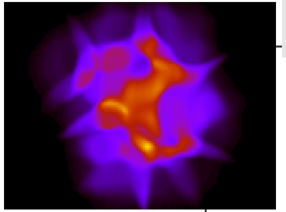




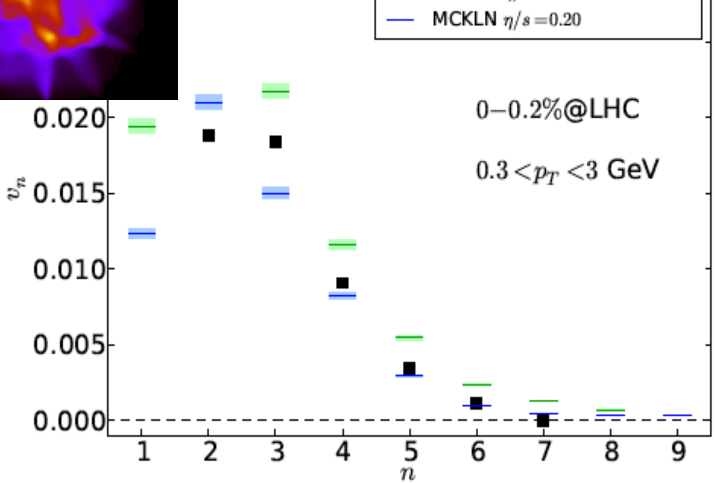
All harmonics appearing with different weights.

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

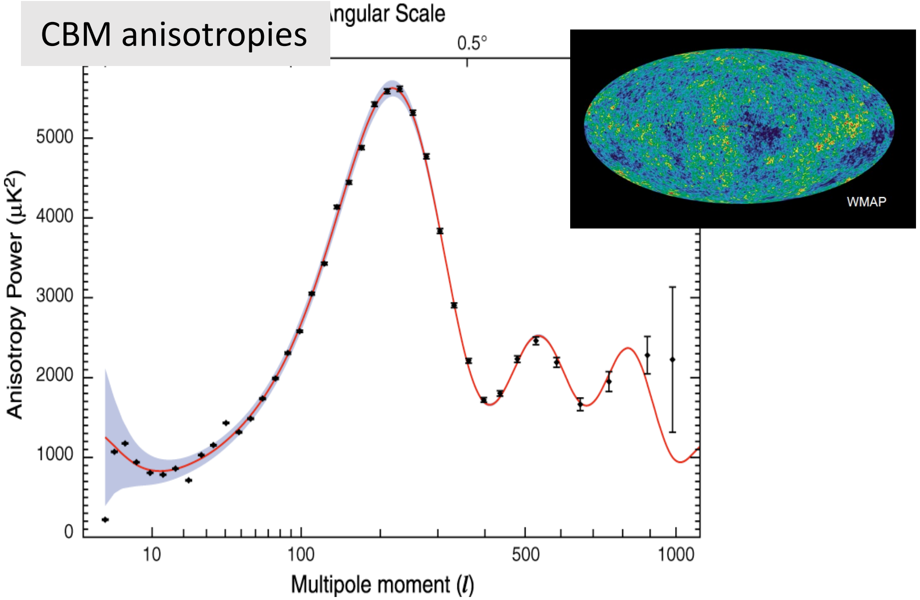
Going deeply into Hot QCD matter



v_n anisotropies



CBM anisotropies



- Initial QCD quantum fluctuations
- T dependence of η/s and $D_s(T)$
- Equation of State
- Freeze-out dynamics

Keeping size and time of QGP

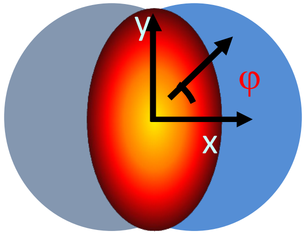
- Spectral Index
- Standard Model Matter
- Cold Dark Matter
- Dark Energy
- Hubble Constant

Keeping Age and Flatness of the Universe

Go to WMAP website and play Build a universe…

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

Transverse view



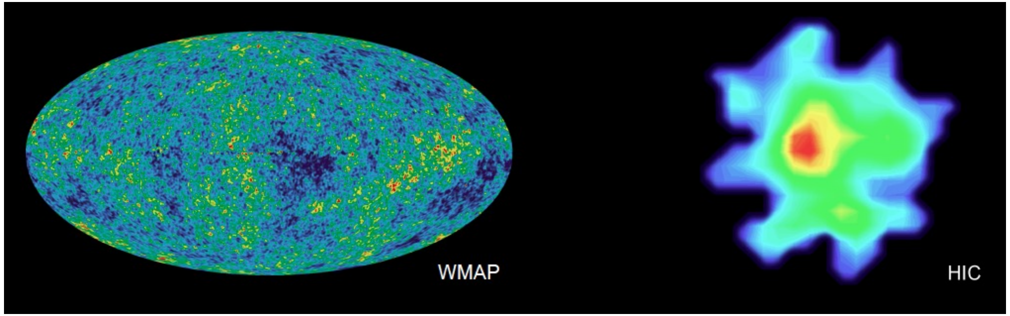
Relativistic HIC

in ’90s, ’00 till about 2005

Anisotropies only with

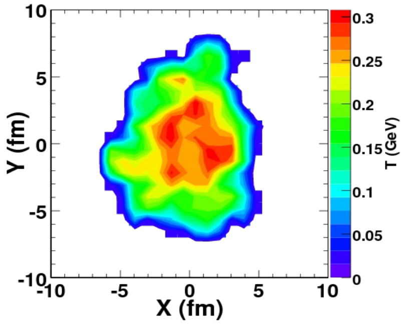
even parity due to symmetry

→ v_2 elliptic flow

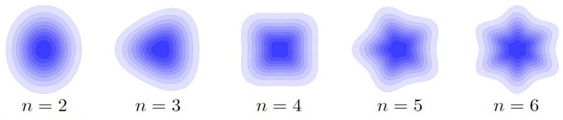


v_n(light) vs v_n (charm) - ebe

Transverse view of HIC,nowdays

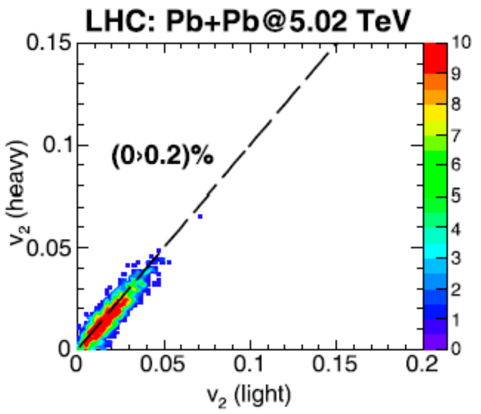


When including fluctuations, all moments appear:

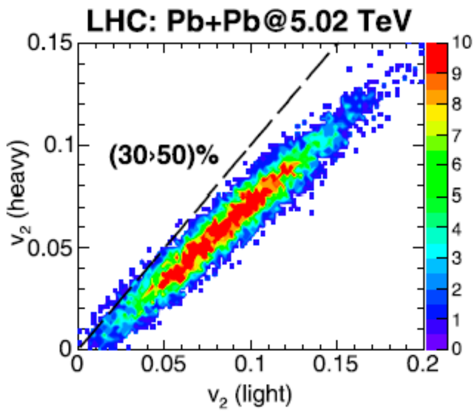


All harmonics appearing with different weights.

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



ultra-central



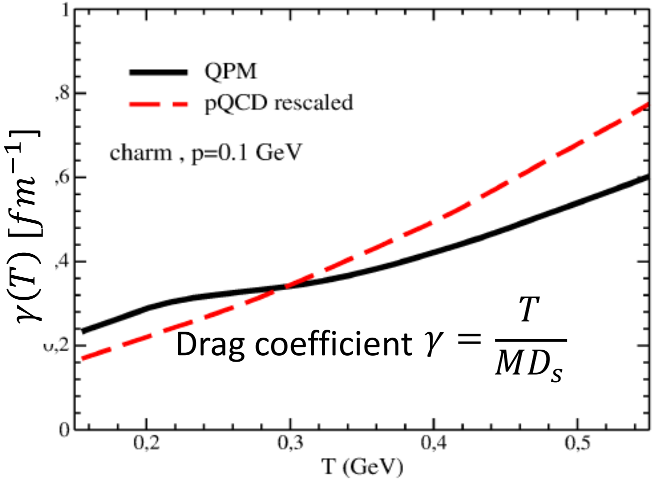
semi-central

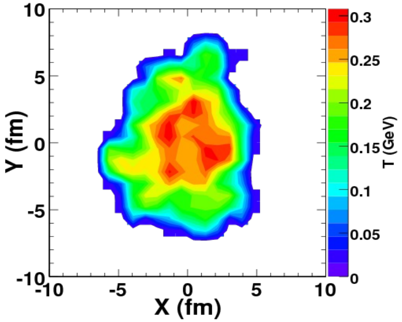
HL-LHC allows to access v_n light-HQ correlation

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

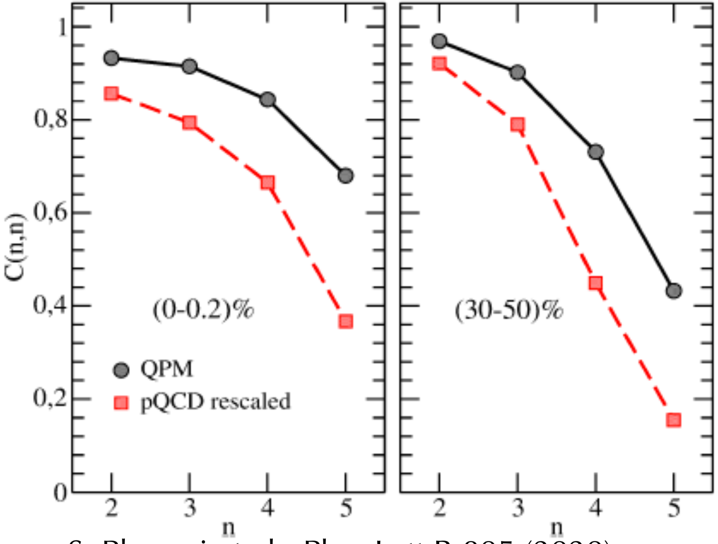
→ Much more precise determination of the strength interaction: drag $\gamma \sim 1/D_s$

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





Very large sensitivity to T dep. of Ds

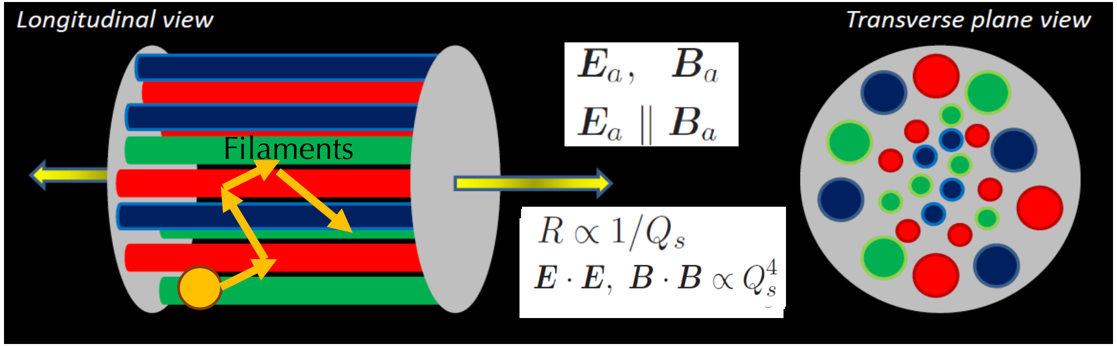


S. Plumari et al., Phys.Lett.B 805 (2020)

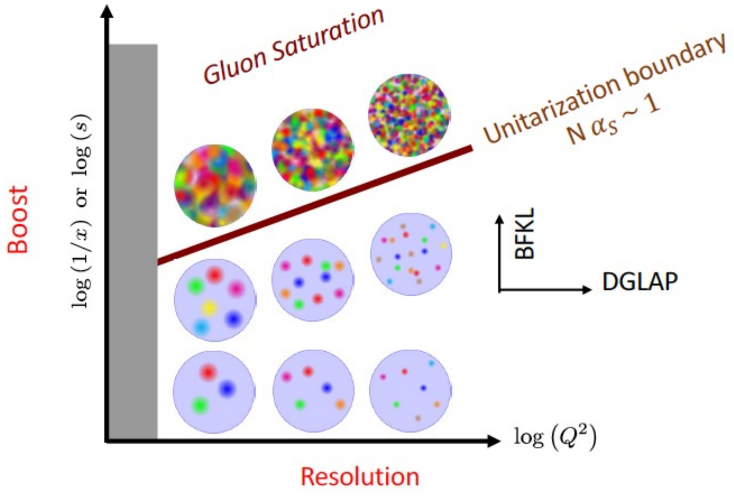
All at fixed $R_{AA}(p_T)$

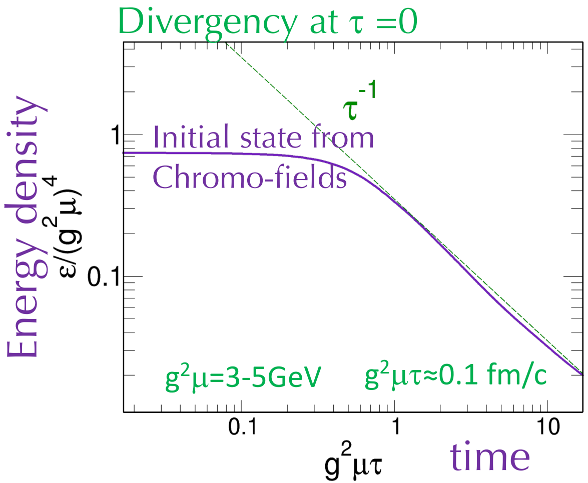
HQ probe of CGC/Glasma phase $0^+ < t < 0.3$ fm/c

Color Glass Condensate (CGC) as high-energy limit of QCD (non-linear evolution at low x) in the BFKL direction in the plane $[Q^2, x]$?



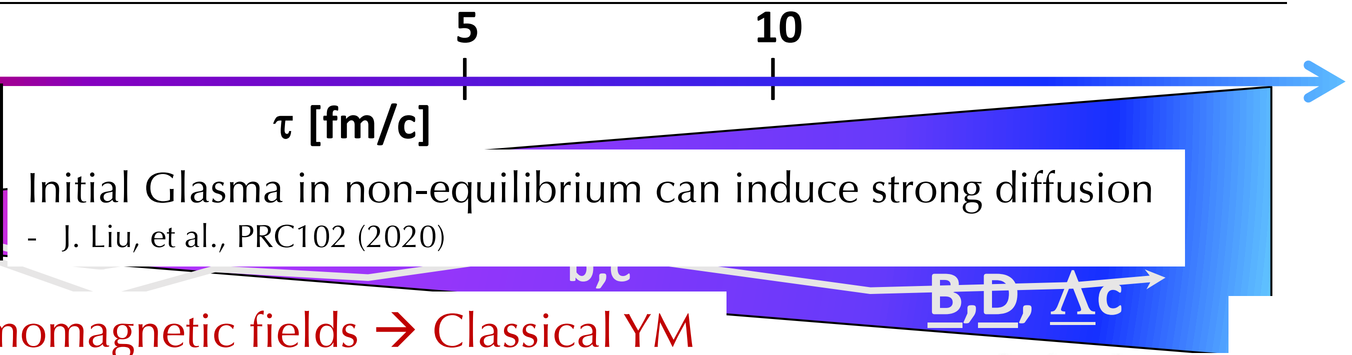
$Q_s \sim A^{4/3}$

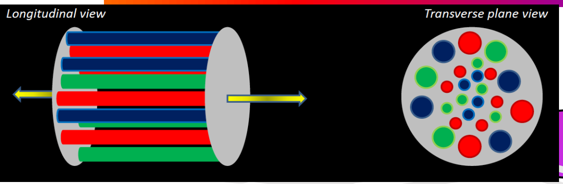




- Solving the t=0 divergency $\varepsilon \sim \frac{1}{\tau}$ (≈ initio of the Collision Universe)
- The unknown very early stage would not destroy our current picture, but we look for signatures to spot from this phase [~ Early Universe]

Impact of Glasma phase



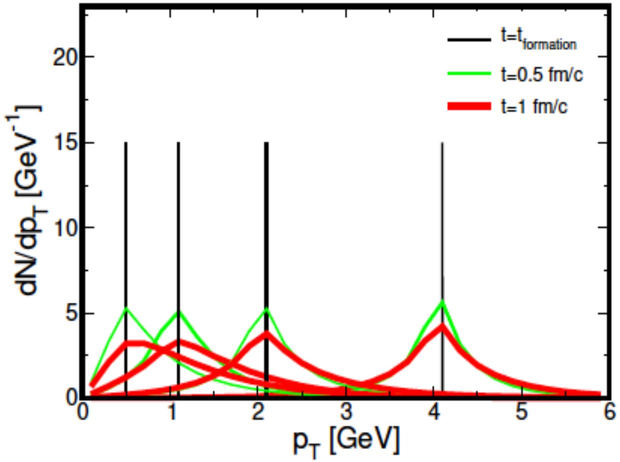


Initial Glasma in non-equilibrium can induce strong diffusion

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

Large intense initial chromomagnetic fields → Classical YM

Static box- SU(2)



Solving classical Yang-Mills

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

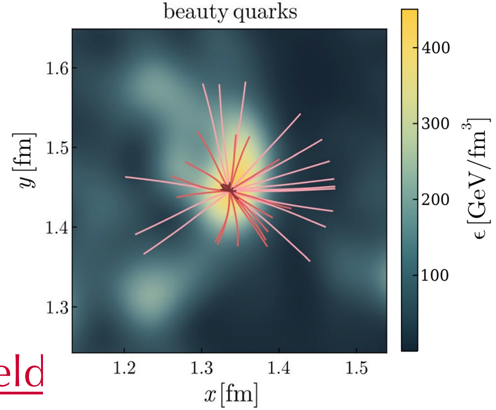
$$\frac{dE_i^a(x)}{dt} = \sum_j \partial_j F_{ji}^a(x) + \sum_{b,c,j} f^{abc} A_j^b(x) F_{ji}^c(x),$$

Heavy quark in the chromo magnetic field

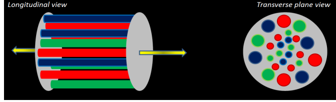
$$\frac{dx_i}{dt} = \frac{p_i}{E},$$

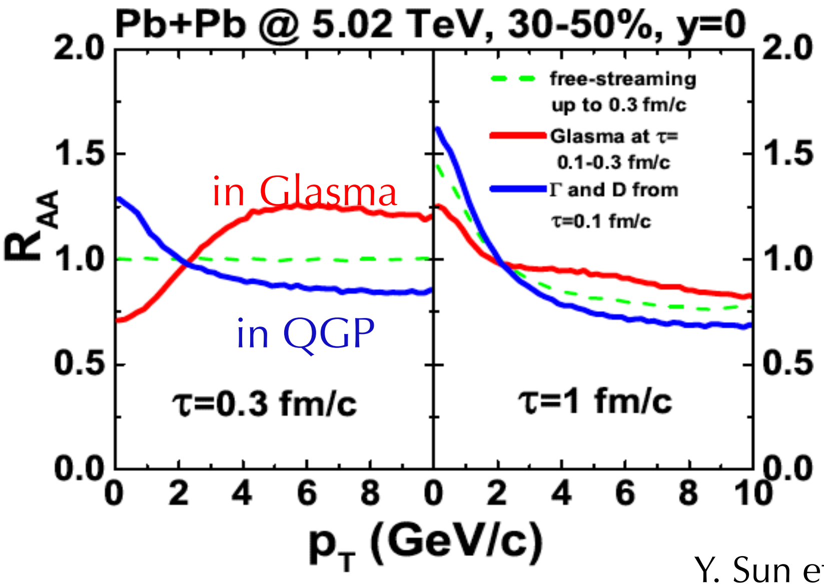
$$E\frac{dp_i}{dt} = Q_a F_{i\nu}^a p^\nu,$$

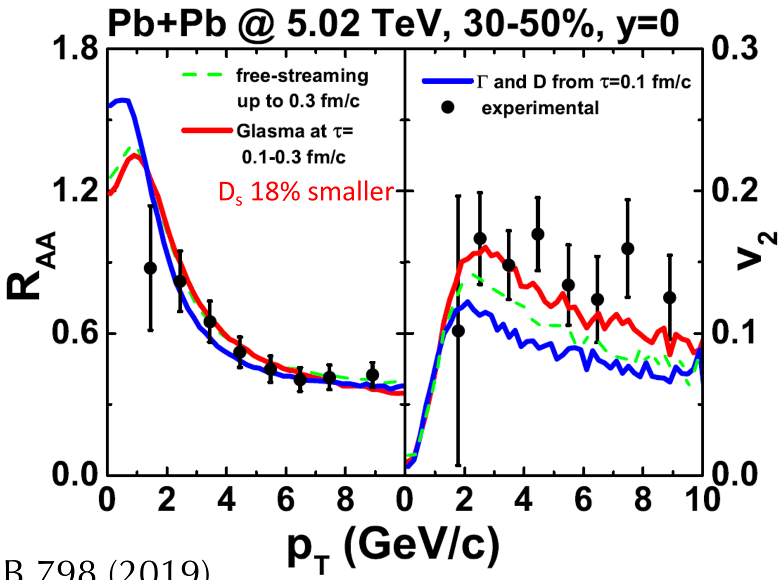
$$E\frac{dQ_a}{dt} = -Q_c \varepsilon^{cba} A_b \cdot p,$$



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



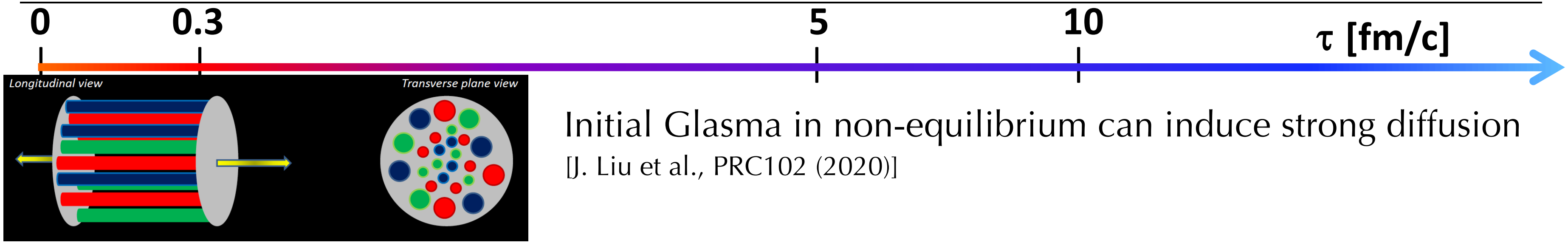




Y. Sun et al.,PLB 798 (2019)

- ❖ **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]

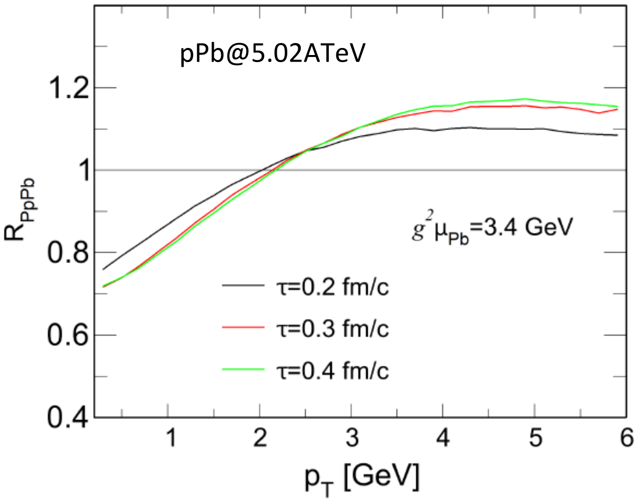
Impact of Glasma phase

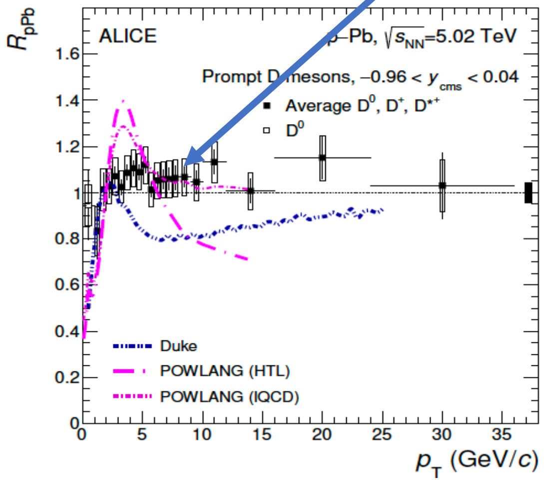


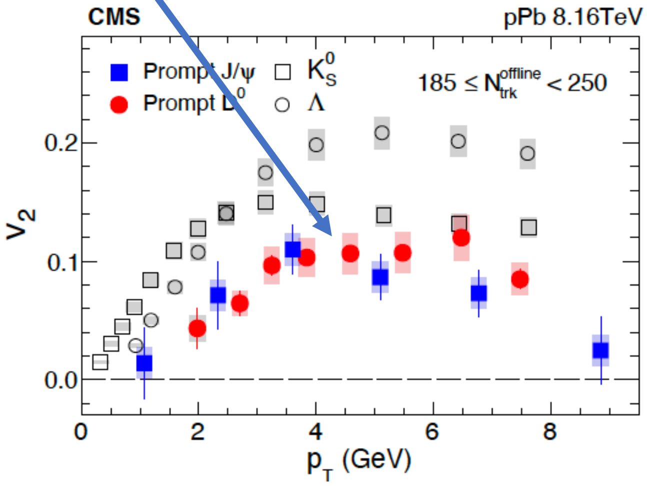
Initial Glasma in non-equilibrium can induce strong diffusion
[J. Liu et al., PRC102 (2020)]

In pA collision it could solve the “puzzle”:
R_{pA} ~ 1 and large v_2 of D meson

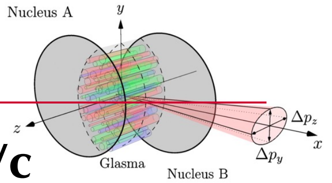
Phenomenological impact





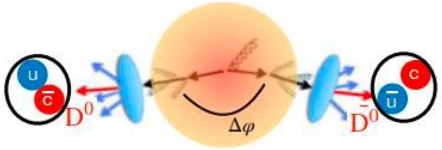


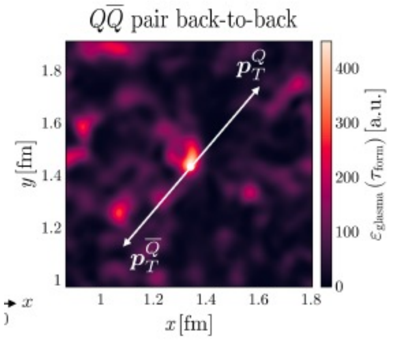
Glasma impact on angular $Q\bar{Q}$

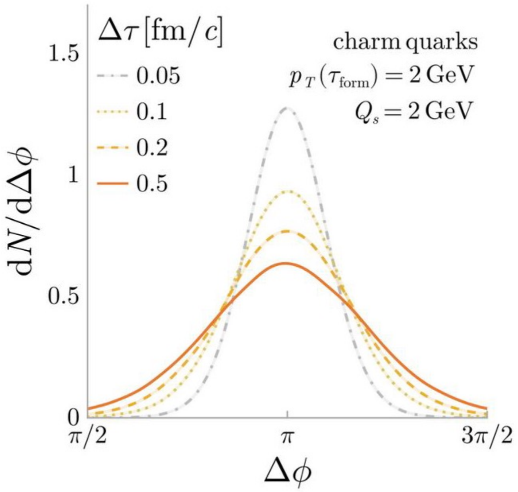


First study of azimuthal $Q\bar{Q}$ correlation: large decorellation **in only 0.2 fm/c**

Significant effect of glasma on HQ!





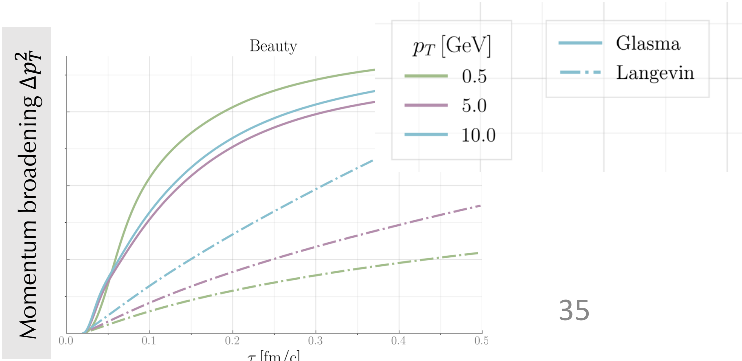


Nearly **identical for bottom** despite mass [smaller t_{form}]

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

- identify Glasma phase
- solve the puzzle od R_{pA} ~1 and v_2 large

Calculation in SU(3) +longitudinal expansion



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

Summary & Perspectives

❖ Open HF set up a strong connection among LQCD,NREFT/phenomenology/exp. observables:
- large non-perturbative interaction: Ds(T):
  agreement of phenomenology to LQCD?! close to AdS/CFT? validity of NREFT/ QCD at finite T?!
- hadronization reveals pp@TeV much closer to AA than e^+e^- or e^-p!?

❖ **It is a Phase of Transition to a new PROGRESS**:
- new LQCD results for $D_s(T)$ → smaller than previous average estimate (τ_{th} (charm)~ 1-2 fm/c)
- better identify impact of baryon HF hadronization (large Λ_c/D) on estimate of $D_s(T)$
- Precision data @*low pT* | *new observables: R_{AA} (Λ_c), v_2 (Λ_c), light-HF v_n correl.,$D\bar{D}$ angular corr.*
  | *extension to bottom* | ***multicharm*** production (**ALICE3**)→ breakthrough

❖ Open HF can have a relevant interplay with developments of Glasma studies [especially for pA]

Back-up Slide

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

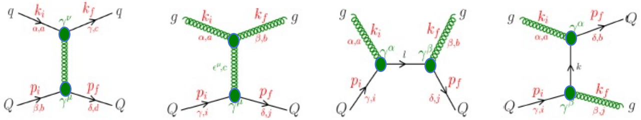
Field interaction $\varepsilon - 3p \neq 0$

Collision term gauged to some η/s≠ 0

Equivalent to viscous hydro at η/s ≈ 0.1

HQ evolution

$$p^{\mu}\partial_{\mu}f_{Q}(x,p)=\mathcal{C}[f_{q},f_{g},f_{Q}](x,p)$$



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

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

Multicharm production + PbPb → OO

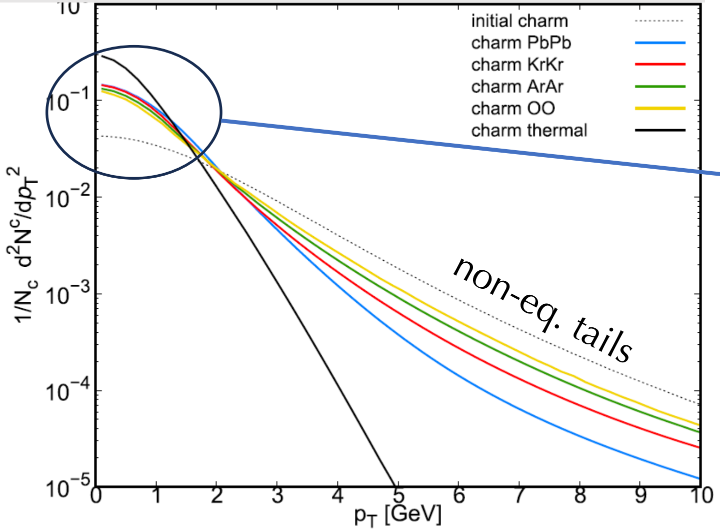
$\Xi_{cc}^{+,++}$, Ω_{scc}, Ω_{ccc}

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

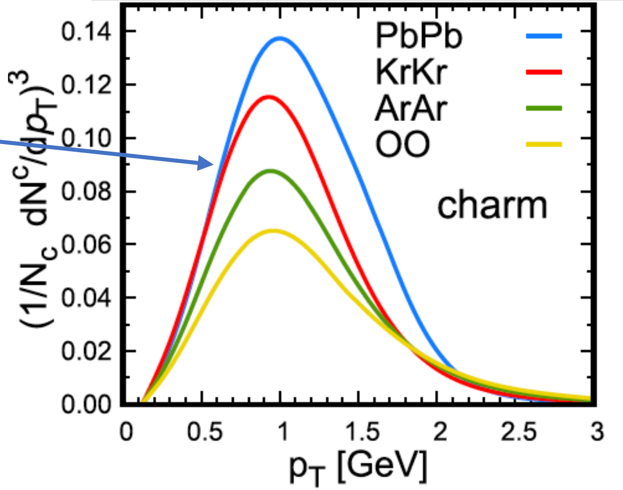
- Understand HQ in medium hadronization: [pure recombination , no fragmentation at low p_T at least]
- Ω_{ccc} very sensitive (to cubic power) to $(dN_{charm}/dp_T)^3$

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

Evolution of p_T charm vs system size

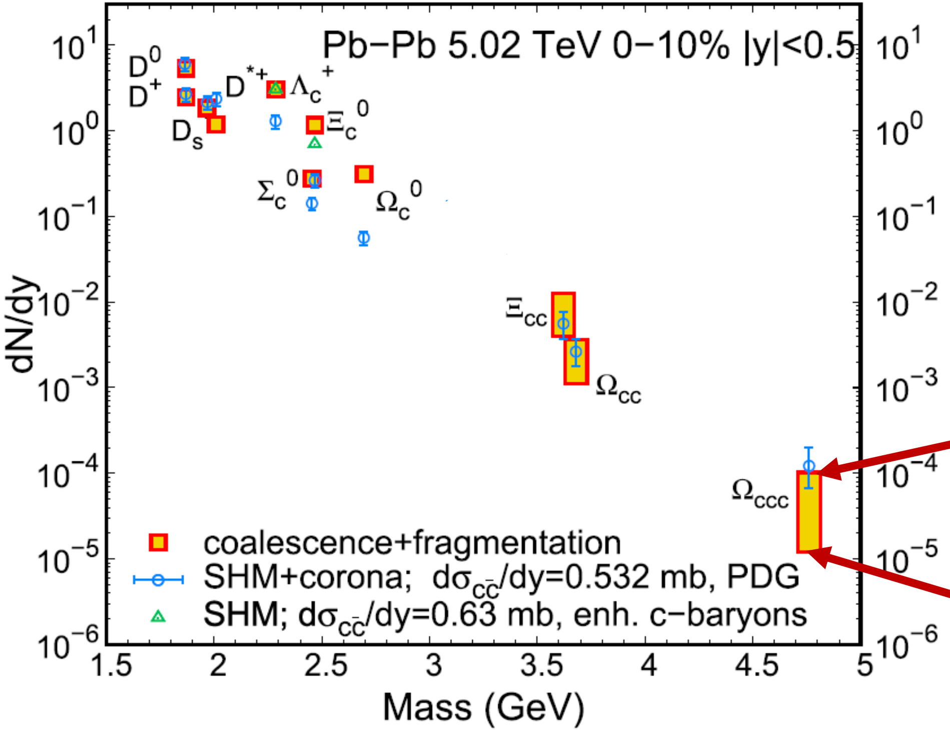


cubic of renormalized charm p_T distrib.



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

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

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

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

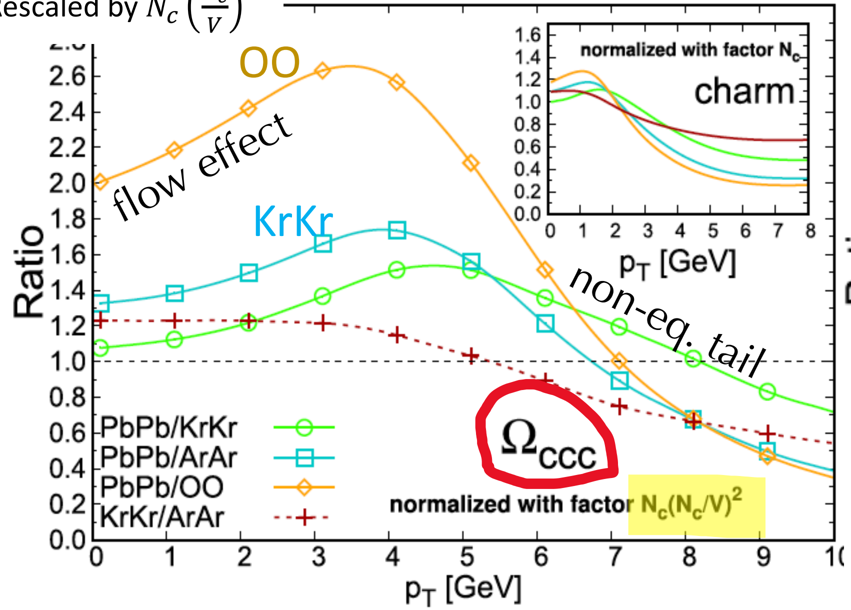
realistic dN_{charm}/dp_T from $D_s(T)$

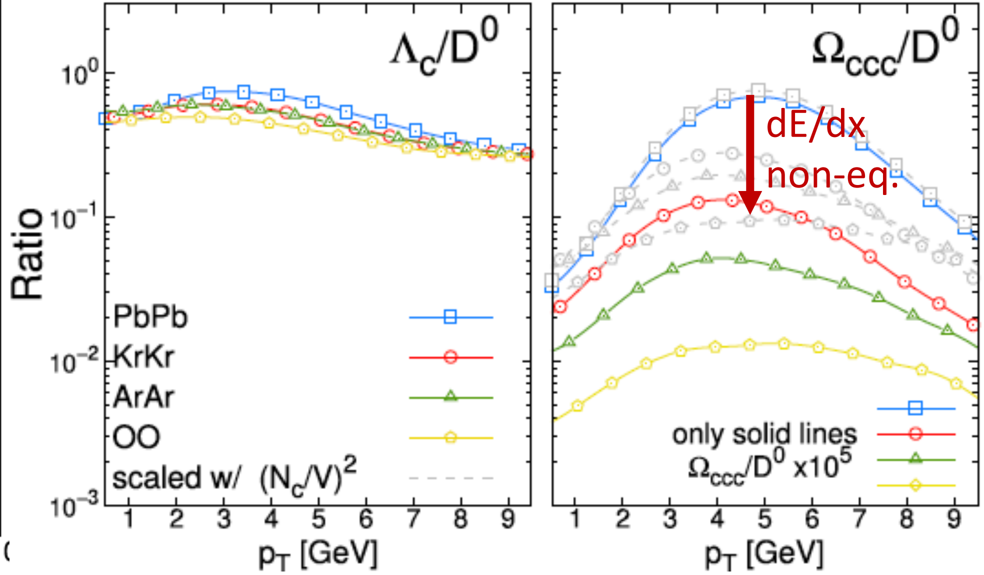
- Makes a I order of magnitude difference depending on degree of equilibirum, while very small effect on D, Λ_c ~(dN_{charm}/dp_T), also due to charm # conservation & confinement

Ω_{ccc} p_T evolution from PbPb to OO

Minissale et al., EPJC84(2024)

Rescaled by $N_c \left(\frac{N_c}{V}\right)^2$



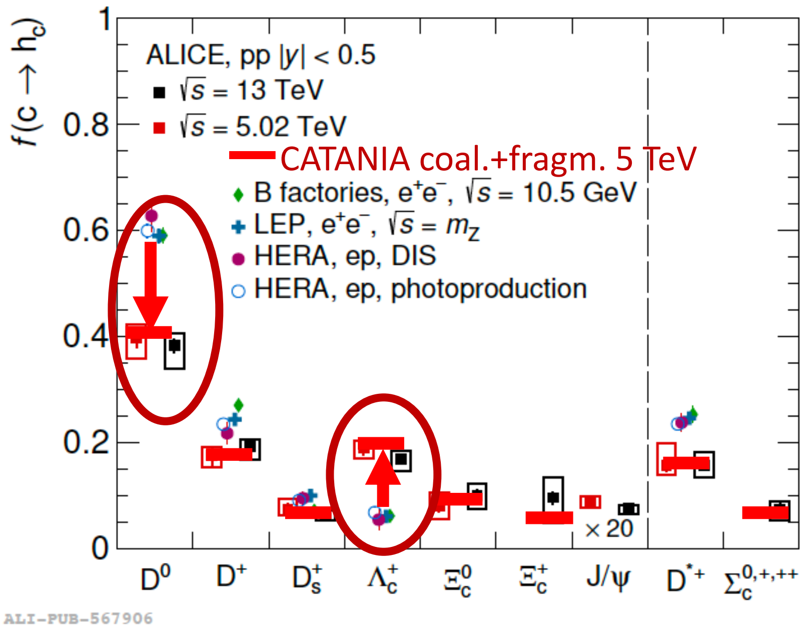


Deviation from scaling $N_c \left(\frac{N_c}{V}\right)^2$ due to different final p_T-charm distribution wrt PbPb

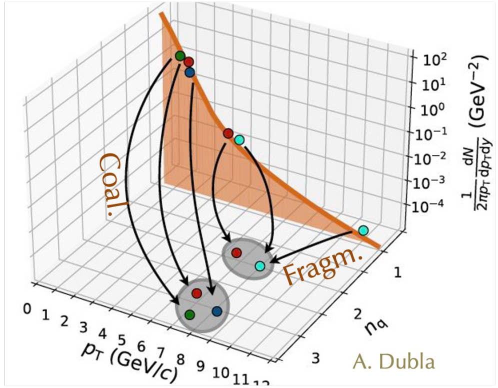
Ω_{ccc} p_T spectrum evolution with system size unveil direct information of charm dN_c/dp_T with much larger sensitivity w.r.t. D^0 or Λ_c → precise info on interaction $D_s(T)$

ALICE3

"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
- ➢ OK SHM-RQM for Λc and D's
- ➢ Large Ξ_c , Ω_c only in coalescence, lack of yield in PYTHIA, SHM-RQM,… large error bars



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

QPM (N_f=2+1) extension to QPMp (N_f=2+1+1)

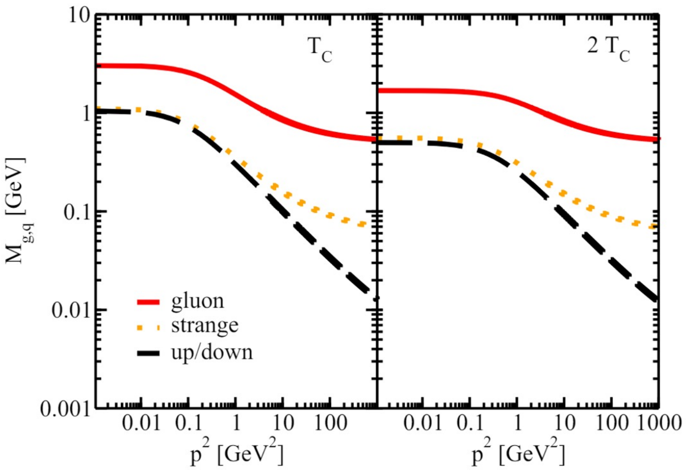
From Dyson-Schwinger (~ PHSD group in N_f=2+1)

$$M_g(T,\mu_q,p) = \left(\frac{3}{2}\right)\left(\frac{g^2(T^\star/T_c(\mu_q))}{6}\left[\left(N_c+\frac{1}{2}N_f\right)T^2+\frac{N_c}{2}\sum_q\frac{\mu_q^2}{\pi^2}\right]\left[\frac{1}{1+\Lambda_g(T_c(\mu_q)/T^\star)p^2}\right]\right)^{1/2}+m_{\chi g}$$

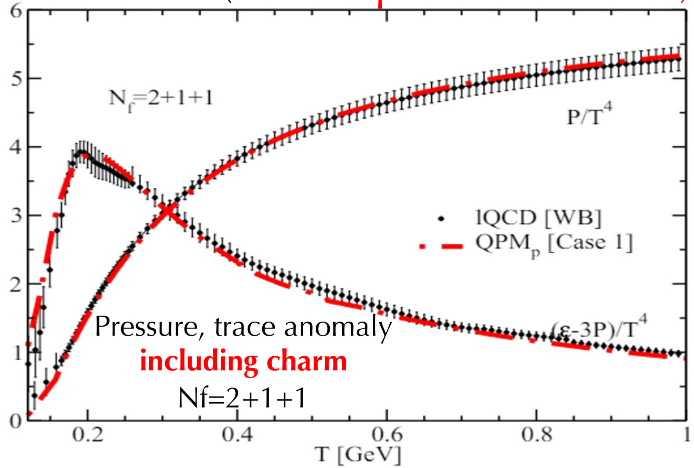
$$M_{q,\bar{q}}(T,\mu_q,p) = \left(\frac{N_c^2-1}{8N_c}g^2(T^\star/T_c(\mu_q))\left[T^2+\frac{\mu_q^2}{\pi^2}\right]\left[\frac{1}{1+\Lambda_q(T_c(\mu_q)/T^\star)p^2}\right]\right)^{1/2}+m_{\chi q}$$

C. S. Fischer, J. Phys. G, R253 (2006)
H. Berrehrah, W. et al., PRC 93(2016)
M.L. Sambataro et al. e-Print: 2404.17459

Momentum dependent masses
p >> Λ_{QCD} $m_{u,d,s}$ → current masses



QPM extended from Nf = 2+1
to Nf = 2 + 1 + 1 (charm quark is included)

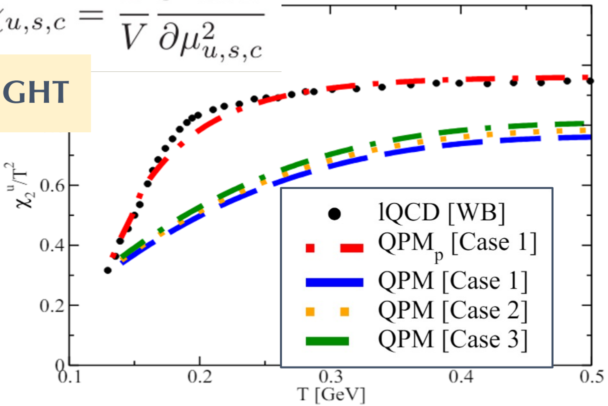


$m_{u,d,s}(p)$ expected but solves also a know issue…

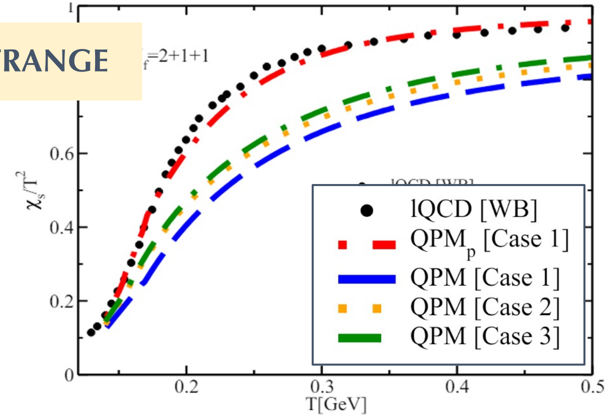
Quark susceptibility from QPM to QPMp

$$\chi_{u,s,c} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial \mu^2_{u,s,c}}$$

LIGHT



STRANGE



Case 1: $m_c = 1.5\ GeV$

Case 2: $m_c^2 = m_{c0}^2 + 1/3 g^2 T^2$ with $m_{c0} = 1.3\ GeV$

Case 3: $m_c(T)$ fixed by charm χ_2^c

$$\chi_2^c = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial \mu_i^2}$$

Quite different quark susceptibility χ_2^q even if correspond to same $\varepsilon_{lQCD}(T)$?!

For $m(p) = const.$

$$\frac{\varepsilon}{T^4} \sim \left(\frac{m}{T}\right)^3 K_1\left(\frac{m}{T}\right) + 3\left(\frac{m}{T}\right)^2 K_2\left(\frac{m}{T}\right)$$

$$\chi_2^q \sim \left(\frac{m}{T}\right)^2 K_2\left(\frac{m}{T}\right)$$

χ_2^q weights higher p of the f(p) wrt ε

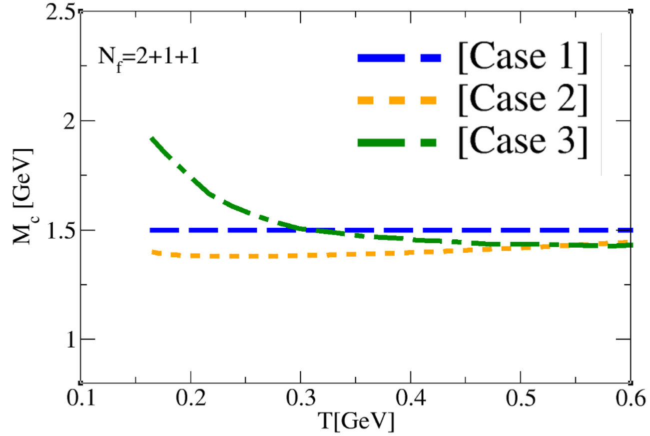
with m(p) one can have ε(T) like that of a massive gas with χ_2^q of a lighter mass gas

Citare non diagonaliArticolo 23 + talk sessione

M.L. Sambataro et al. e-Print: 2404.17459

QPM (N_f=2+1) extension to QPMp (N_f=2+1+1)

Extending QPM from **Nf = 2+1**
to **Nf = 2 + 1 + 1** **charm included**



Case 1: $m_c = 1.5\ GeV$

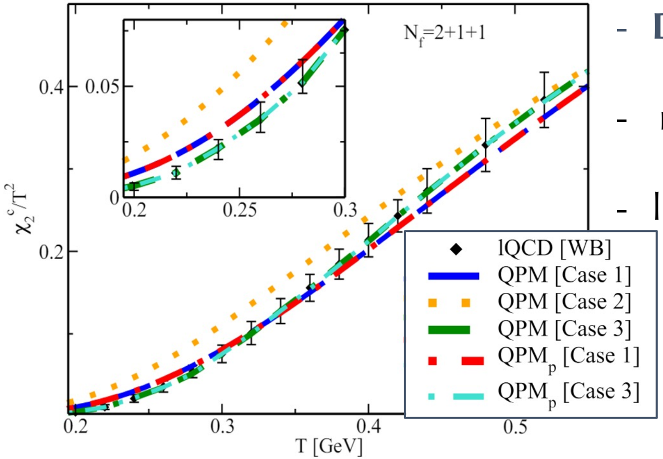
Case 2: $m_c^2 = m_{c0}^2 + 1/3 g^2 T^2$ $[m_{c0} = 1.3\ GeV]$

Case 3: $m_c(T)$ fixed by charm χ_2^c(T)

M.L. Sambataro et al. e-Print: 2404.17459

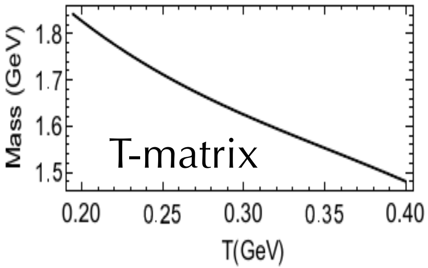
CHARM QUARK SUSCEPTIBILITIES

$$\chi_2^c = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial \mu_i^2}$$



- **Disfavored**: increasing m_C(T) and m_C smaller than 1.5 GeV
- mc (standard valute) not bad!

- lQCD data overestimated for T≈0.2-0.3 GeV with constant m_C

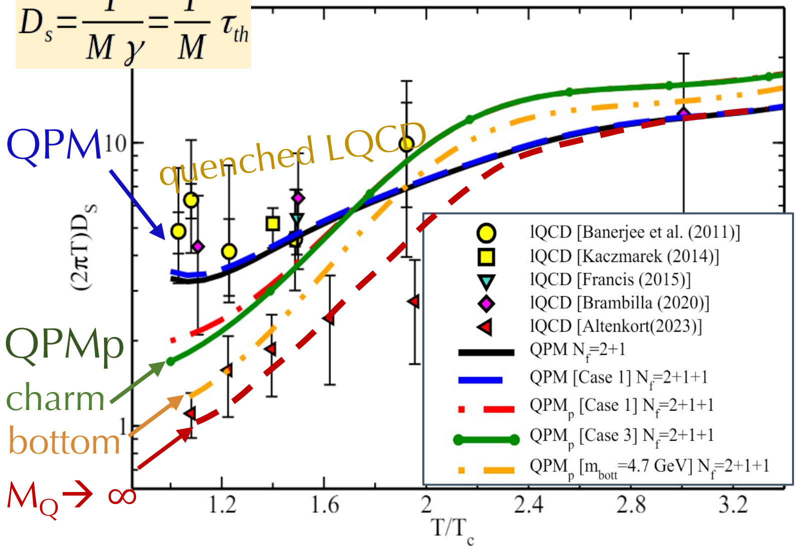


- Susceptibility seems to imply a decreasing m_C(T) from 1.9 GeV at T_C down to 1.5 GeV at $2T_C$: **similar to T-matrix (TAMU)**

Diffusion $D_s(T)$ from QPM to QPMp

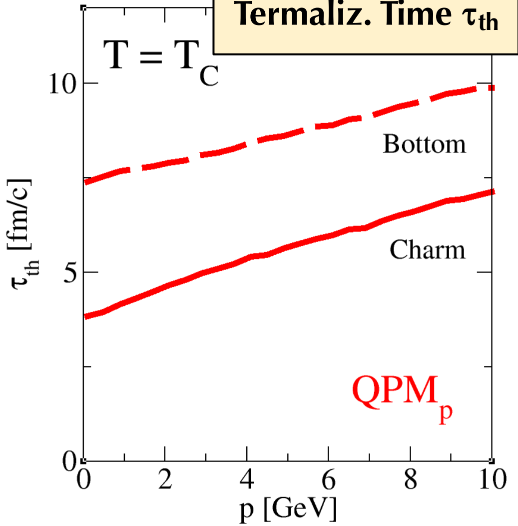
M.L. Sambataro et al. e-Print: 2404.17459

$$D_s = \frac{T}{M\gamma} = \frac{T}{M}\tau_{th}$$



- **QPMp** describes **ε,P, χ_q, χ_s of LQCD** and is **closer than QPM** to D_S to LQCD(new) with dynamical fermions
- Still a signficant mass dependence from charm to bottom not seen in LQCD + Non Rel. EFT
- **Can this new $D_s(T)$ generate predictions for R_{AA}, v_2, v_3 in agreement with experimental data?**

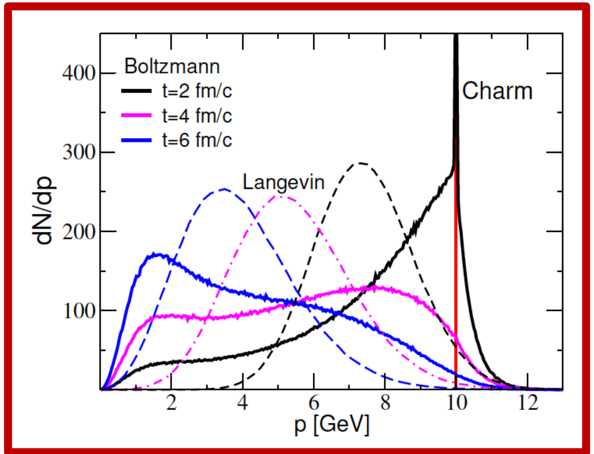
Termaliz. Time τ_{th}

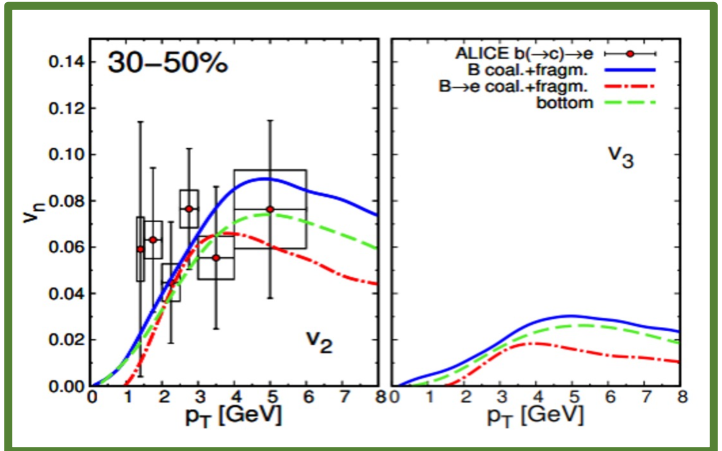


- **For observables is relevant the p-dependence:**
  $T=T_C$ -> 40 % larger τ_{th} (*smaller D_s*) at p~5 GeV, but could be larger: to be done a comparison among different approaches
  [QPMp p-dependence within the Bayesian analisys of Duke group]
- At T_c seems LQCD+NERFT clould lead to a gap wrt Ds calculation from the hadronic part. [Das, Torres-Rincon, 2406.13286[hep-ph]]

Relevance of direct Bottom measurements

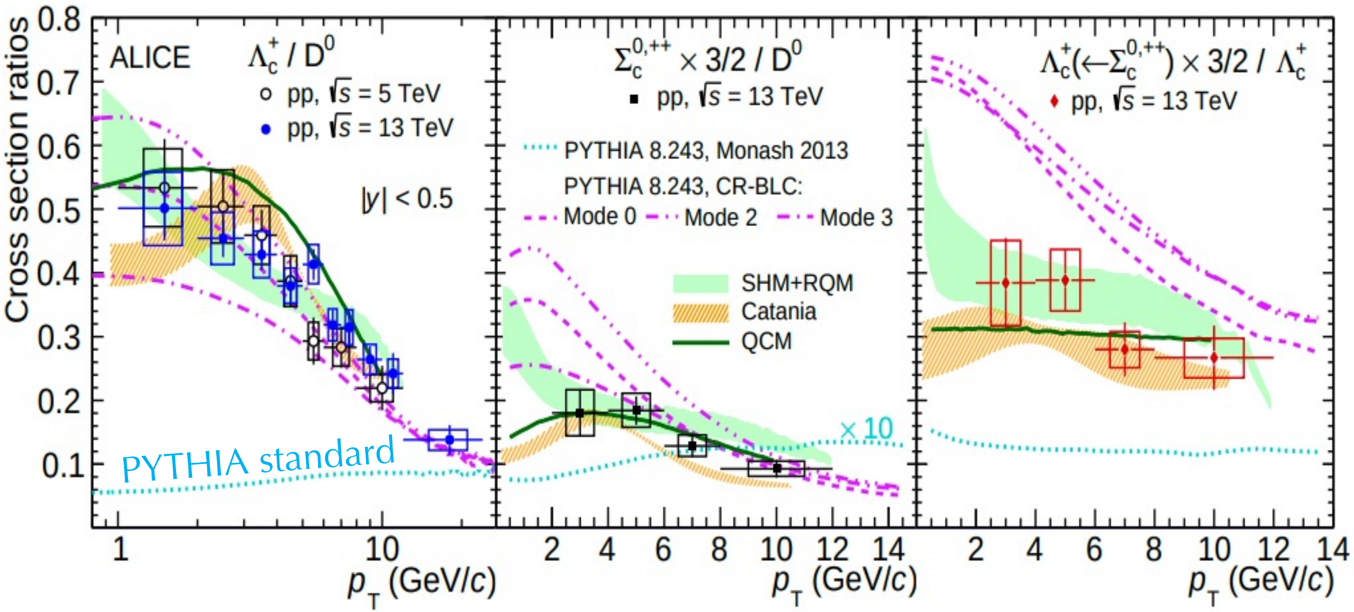
- Quite close to **M→ ∞** & **Non Relativistic** limit
  → more solid comparison to LQCD/NRQCD for $D_s(T)$
- $M_Q(T)$ >> T, gT full **Brownian motion**, satisfy fluctuations dissipation theorem
  → damps uncertainties in transport evolution (Langevin, Boltzmann, Kadanoff-Baym…)
- Impact of **hadronization**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





Going deeper into Λ_c enhancement

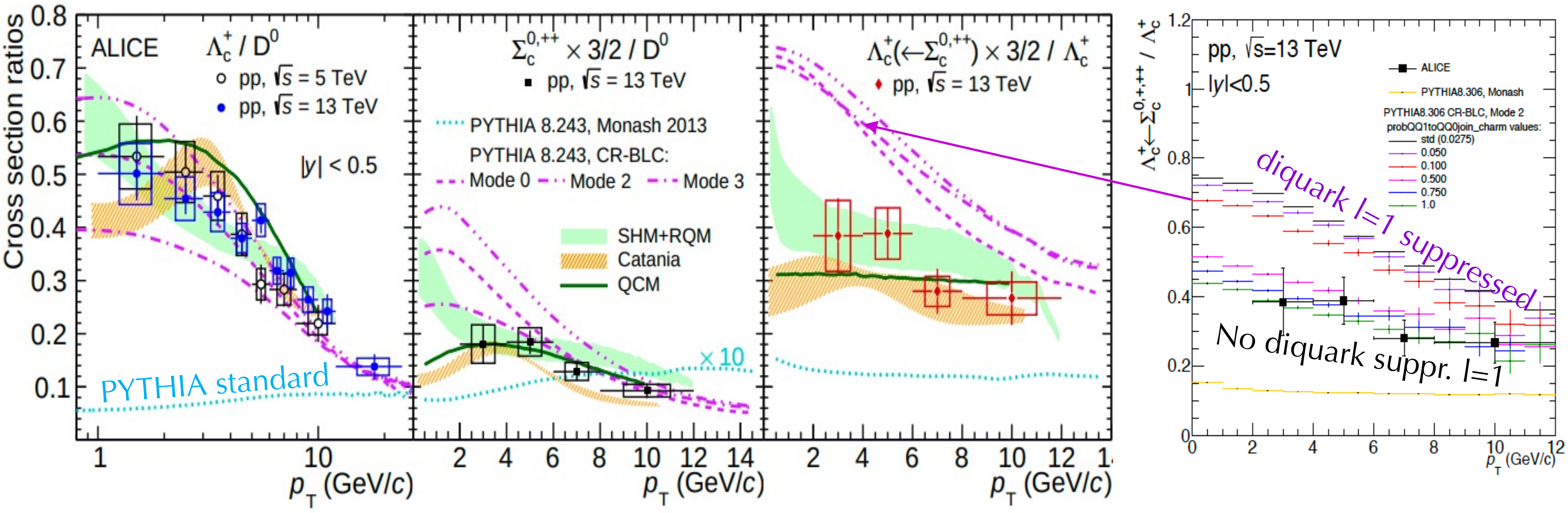
Altmann et al., arXiv 2405.19137



- 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

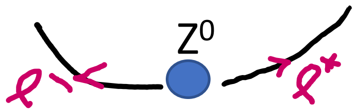


- Catania-coal & SHM-RQM/QCM natural good description of Σ_c/D^0 and $\Lambda_c \leftarrow \Sigma_c$
- PYTHIA-CR too many $\Sigma_c \rightarrow \Lambda_c/D^0$; associated to a suppression of junction **diquark *I=1*** *(set ~* e^+e^- for string di-quark*). Removing it → Agreeement to data of $\Lambda_c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

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

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

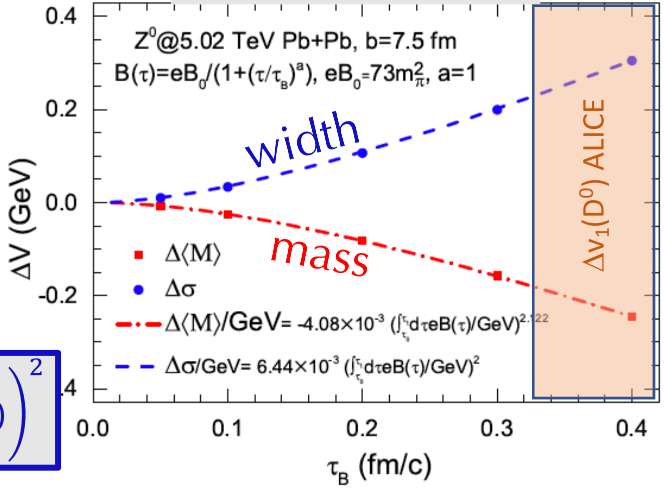
$$\rho(M) = \frac{1}{\pi}\frac{\Gamma/2}{(M-M_0)^2+\Gamma^2/4},$$

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

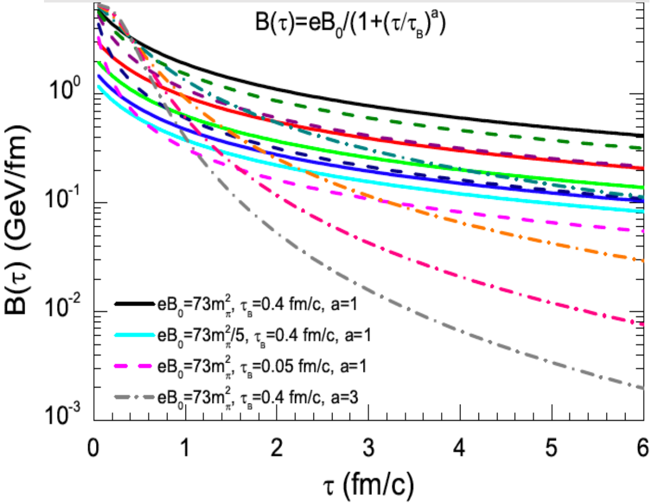
$n=2.16\pm0.16$, $k=-[3.9\pm1.2] \cdot 10^{-3}$

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

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?

On-shell & off-shell dynamics for charm

Extending collision integral to **off-shell dynamics:** solvable in a box at equilibrium

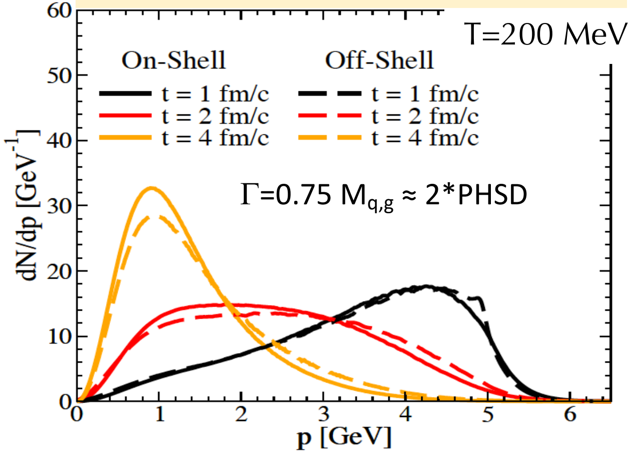
$$C[f] = \int dm_i A(m_i) \int dm_f A(m_f) \times \frac{1}{2E_p} \int \frac{d^3\mathbf{q}}{2E_q(2\pi)^3} \int \frac{d^3\mathbf{q}'}{2E_{q'}(2\pi)^3} \int \frac{d^3\mathbf{p}'}{2E_{p'}(2\pi)^3} \times \frac{1}{\gamma_Q} \sum |\mathcal{M}_Q|^2 (2\pi)^4 \delta^4(p+q-p'-q') \times [f(\mathbf{p}')\hat{f}(\mathbf{q}', m_f) - f(\mathbf{p})\hat{f}(\mathbf{q}, m_i)] \quad (20)$$

Spectral function for q & g

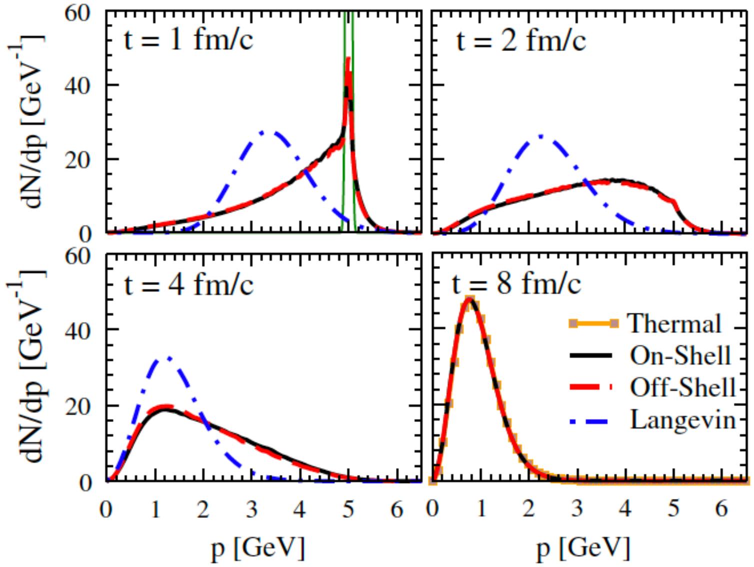
$$A_i^{BW}(m_i) = \frac{2}{\pi} \frac{m_i^2 \gamma_i^*}{(m_i^2 - M_i^2)^2 + (m_i \gamma_i^*)^2}$$

off-shell ≈ PHSD

Evolution of charm at p=5 GeV
ε off-shell=ε off-shell

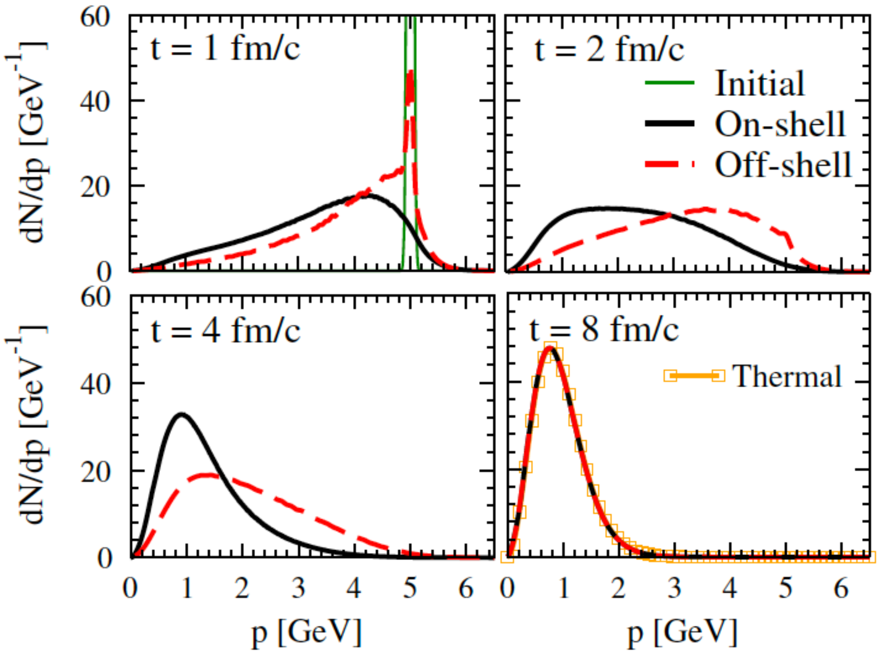


+ a k(p) making the drag off-shell=drag on-shell



M.L. Sambataro et al., EPJC80(2020)

Impact of off-shell dynamics on charm



Bulk is not with the same energy density:

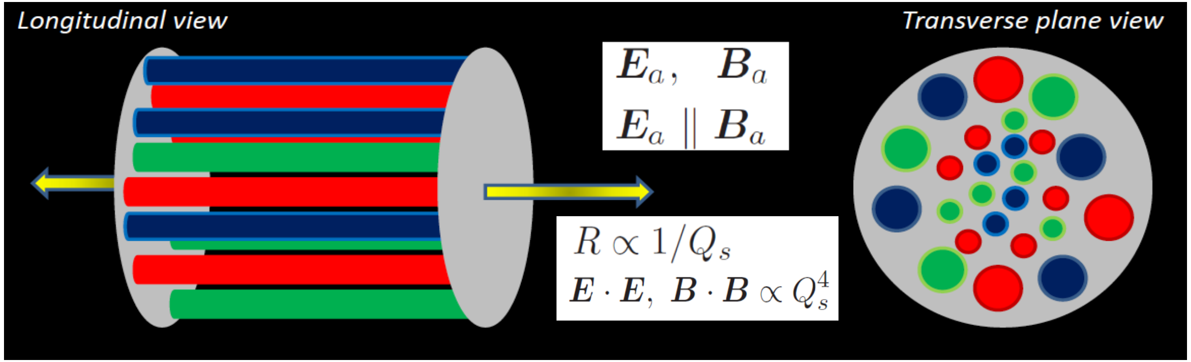
- energy density of off-shell case is smaller
- dynamics is Boltzmann-like: not gaussian

fluctuation areounf the average like in Langevin dynamics

M.L. Sambataro et al., EPJC80(2020)

A first study of HQ in a Glasma

What happens for $0^+<t<0.3-0.5$ fm/c?



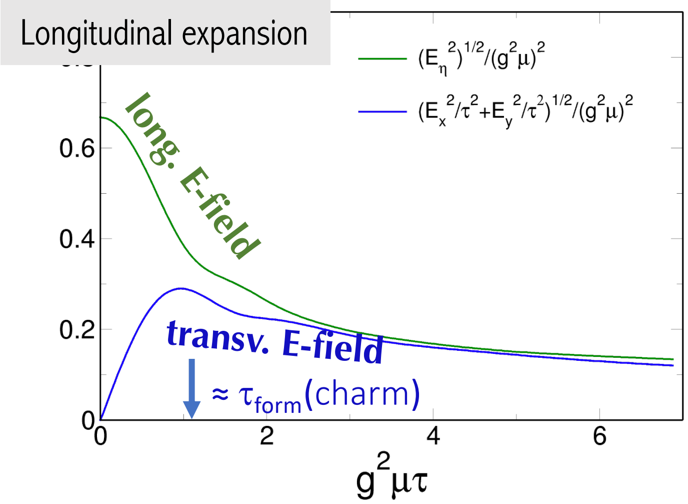
$$\langle \rho_A^a(x_T)\rho_A^b(y_T)\rangle = (g^2\mu_A)^2\delta^{ab}\delta^{(2)}(x_T - y_T),$$

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

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

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

Longitudinal expansion



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

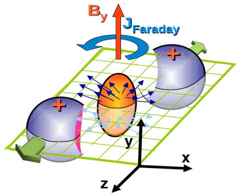
after $\tau \cong Q_s^{-1}$, all components are equal

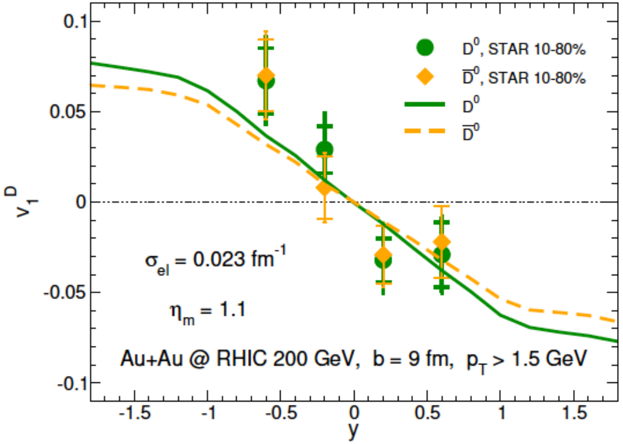
The very early stage has left some imprints?

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

Δv_1 from e.m. field?

Oliva, Plumari, V.G., JHEP 05 (2021)

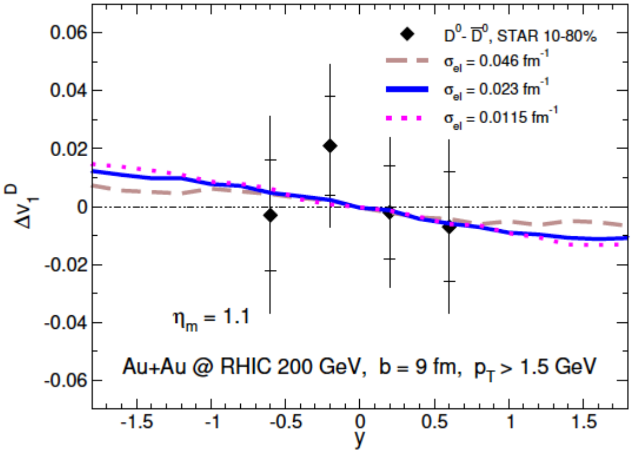




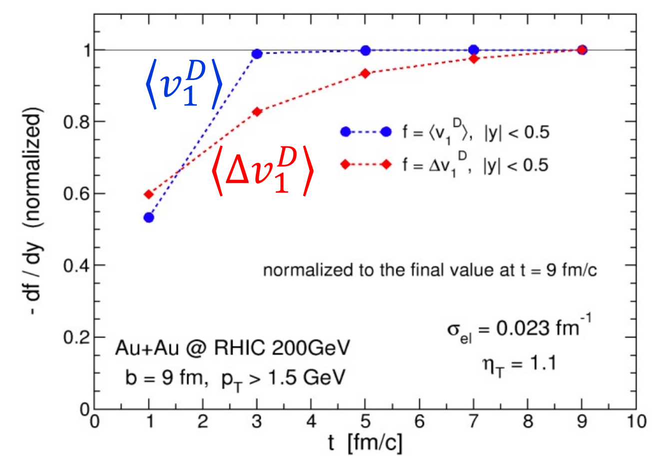
$d(\Delta v_1)/dy|_{exp} = -0.011 \pm 0.024(stat) \pm 0.016(syst)$

$d(\Delta v_1)/dy|_{th.} = -0.01$, L. Oliva et al.

≈ 10 times larger than charged,
similar to S. Das et al., PLB768 (2017)
but could be **also consistent with 0!**



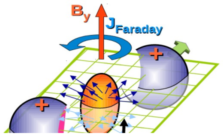
Time evolution

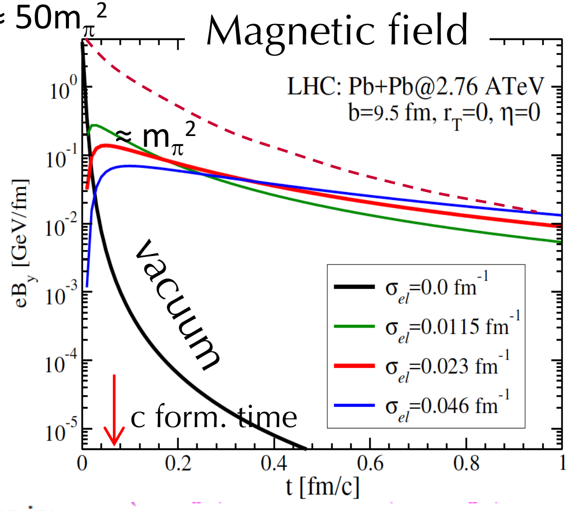


v_1 expected to be more sensitive than v_2 to high T (early time) $D_s(T)$!

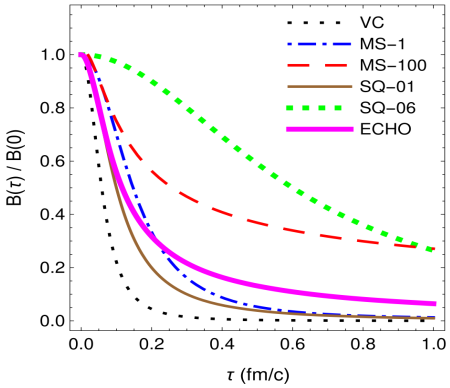
Unexplored…

Electro-Magnetic field

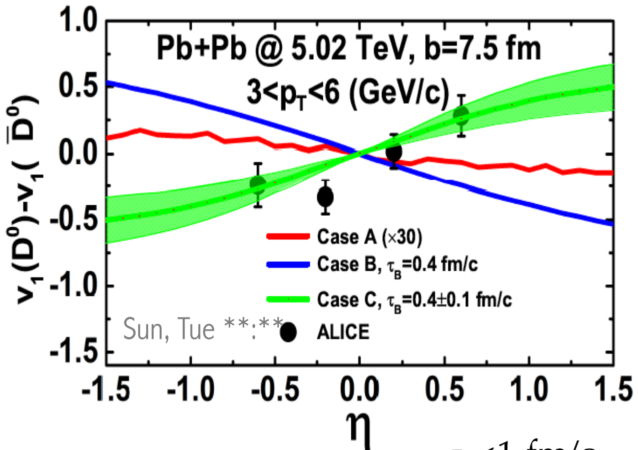




Used for studies of CME



A.Huang et al., PLB777(2018)



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

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

τ <1 fm/c

B(τ) ≈ B(τ)

E_x(τ)> E_x(τ)

like in:

K. Tuchin, PRC 88, 024911 (2013).

K. Tuchin, Adv. High Energy Phys. 2013, 1 (2013).

U. Gürsoy, D. Kharzeev, K. Rajagopal PRC 89, 054905 (2014).

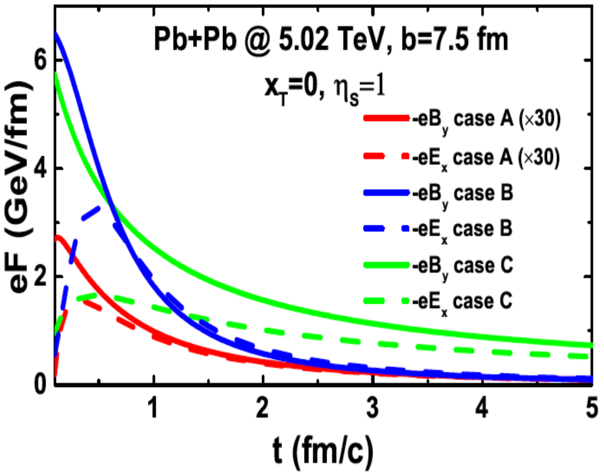
Assumptions:

- Medium σ_{el} at t<0
- Electric Conductivity const. in T
- No Modification in the bulk due to currents
- No e-b-e fluctuations
- Chiral topological charge [arXiv:2002.05047,Tuchin]

Computation of early stage e.m. field is quite an issue:

✧ eB_y(t=0) in the **vacuum:** ≈ 50 m_π^2 @LHC but assumimg a **medium** with σ_{el}≈ 0.02 fm → eB_y(t=0) ≈ m_π^2 @LHC

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 [B_0 at t=0 vacuum value]

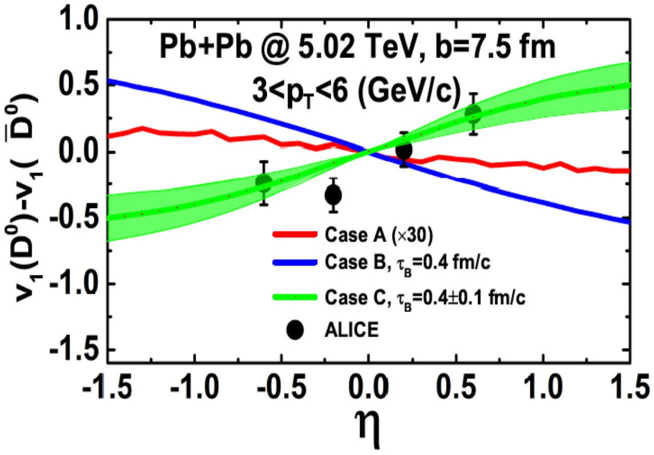
$eB_y(x,y,\tau) = -B(\tau)\rho_B(x,y)$ τ_B=0.4 fm/c

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

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

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

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



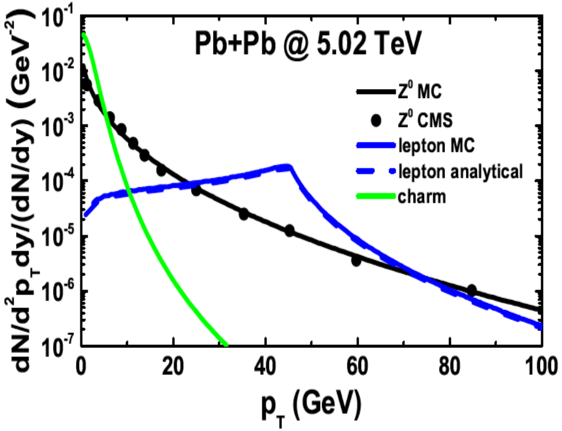
* e.m. field σ_{el} as for RHIC
→ $\Delta v_1(D^0)$ order magnitudes smaller than ALICE data + opposite sign

* e.m. with B_y(t=0) as in vacuum
→ Large $\Delta v_1(D^0)$ but **opposite** direction wrt to data

* e.m. with B_y(t=0) as in vacuum, **$E_x \approx 0.5\ B_y$** (t=0.5-1 fm/c)
→ $\Delta v_1(D^0) \approx$ ALICE Data (1/t ideal MHD)

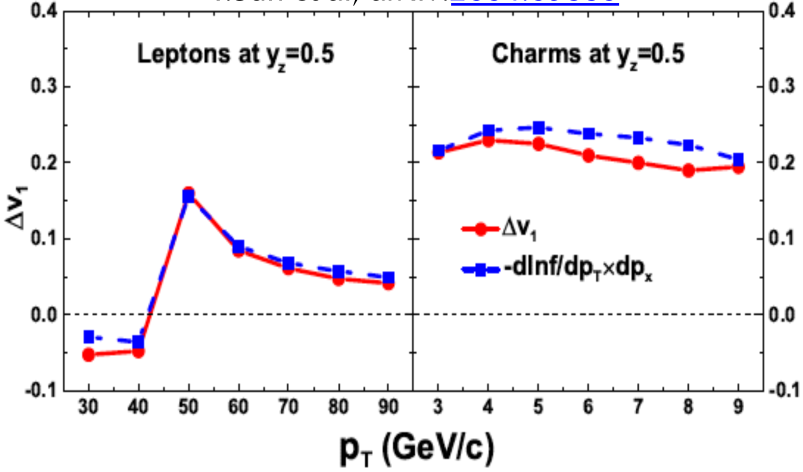
Time derivative of B_y(t) even more relevant than absolute values"

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 + $qE_x - qv_zB_y \approx q(E_x - B_y)$
- Charge 1.5 times larger

Y.Sun et al, arXiv:2004.09880



Surprises:

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 $\Delta v_1(l^+,l^-)$ can be opposite!?

not because wins electric field

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

Peak in $\Delta v_1(l^+,l^-)$ at $p_T \approx 50$ GeV

consistent with the large $\Delta v_1(D^0)$?

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?

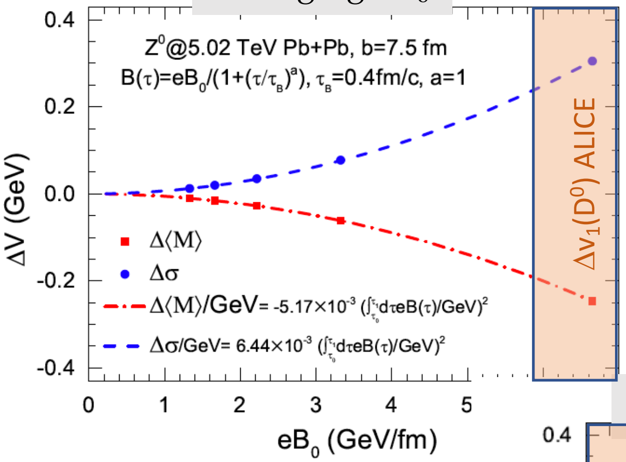
Is there a further way to pin down the e.m field strength?

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

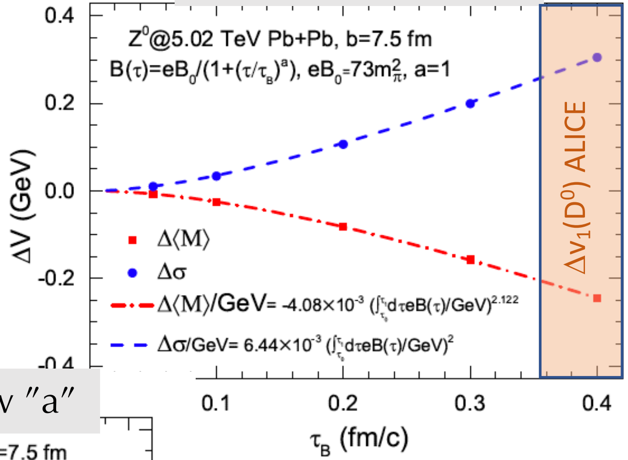
Probing the electromagnetic fields in ultra-relativistic collisions with leptons from Z_0 decay and charmed mesons

Z^0 mass and width modification in AA

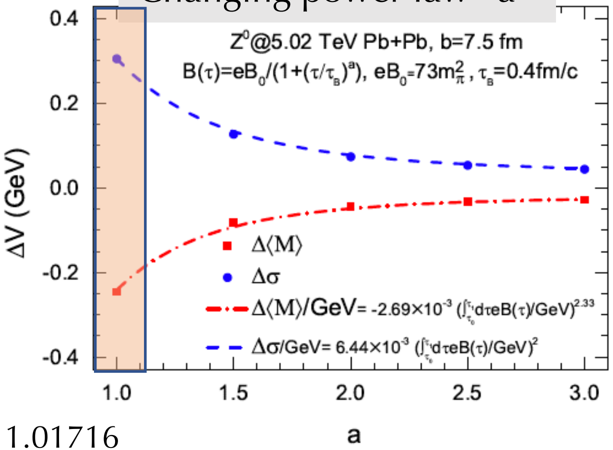
Changing eB_0



Changing lifetime τ_B



Changing power law "a"



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

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, arXiV:2111.01716

To be done vs centralities, systems,…