Heavy Quark dynamics in ultra-relativistic collision: glasma, impact of vorticity, electromagnetic fields

Vincenzo Greco - University of Catania/INFN-LNS

Istituto Nazionale di Fisica Nucleare

Collaborators:
- Y.Sun, V. Minissale, L. Oliva
  S. Plumari, M.L. Sambataro
- M. Ruggieri (Lanzhou)
- S.K. Das (Ghoa)
- D. Avramescu, V. Baran (Bucharest)

"Gluon Plasma Characterisation with Heavy Flavour Probes", ECT*@Trento, 15- 18 November 2021

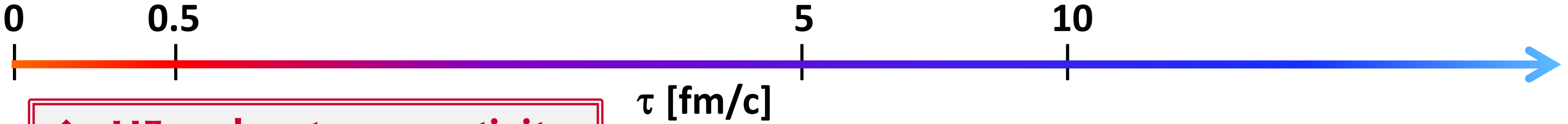
Outline

- ✧ **Heavy Flavor dynamical evolution in QGP**

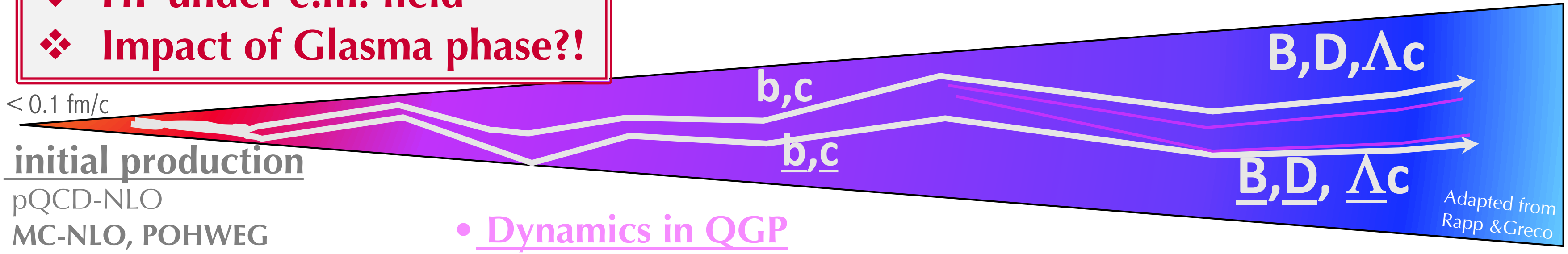
- ✧ **Heavy Flavor as a probe of bulk initial stage:**
  - first studies of the impact of **Glasma** dynamics
  - probe of **bulk vorticity**: initial space distribution of the bulk → large v_1 of D mesons

- ✧ **Impact of e.m. field on v_1 of D^0, $\underline{D}^0$ and $l^{\pm}$ from Z^0 decay:**
  - Δv_1 for heavy quarks: large effect w.r.t. light particle
  - Correlation between Δv_1 of D and *leptons* from Z^0 + ΔM_Z and $\Delta \sigma_z$

Studying the HF in uRHIC



- ❖ HF under strong vorticity
- ❖ HF under e.m. field
- ❖ Impact of Glasma phase?!



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

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

- **Dynamics in QGP**
  - Themalization
  - **Transp. Coeff. of QCD matter $D_s(T)$**
  - Collisional & Radiative

[Sambataro, Tue 10:30]

- **Hadronization**
  - coalescence and/or fragm.
  - Not really know even in pp,pA,AA

[Plumari, Tue 17:30]

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 $\varepsilon - 3p \neq 0$

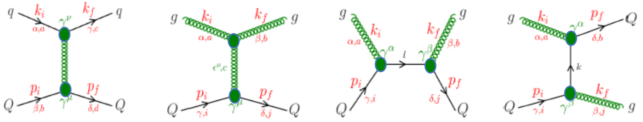
Collision term gauged to some η/s≠ 0

Equivalent to viscous hydro at η/s ≈ 0.1

See M.L. Sambataro talk, Tue 10.:30

HQ evolution

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



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

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

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

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

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

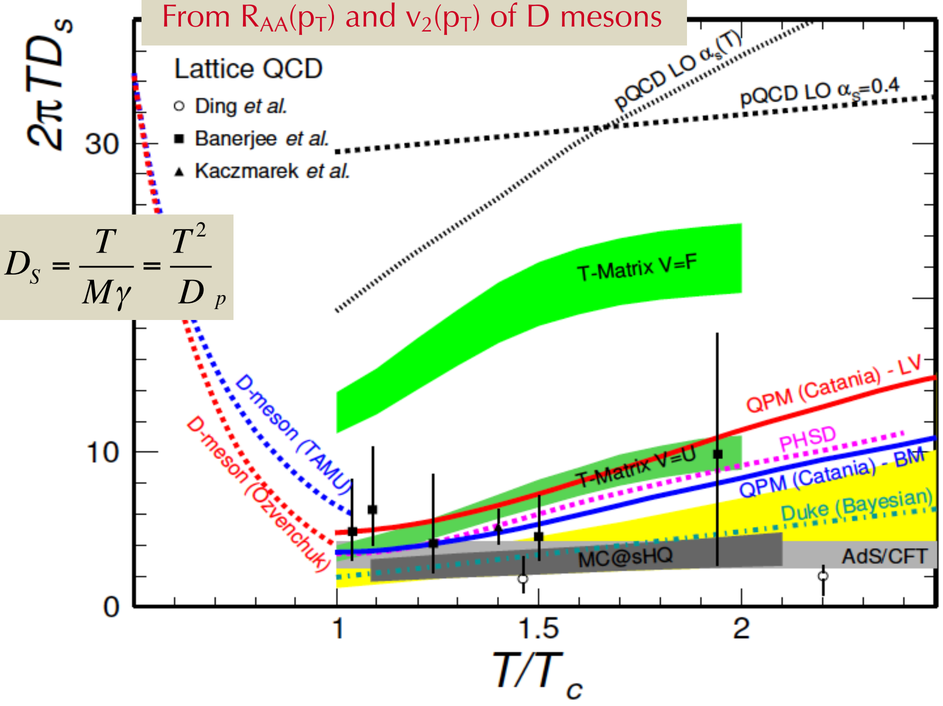
Impact of off-shell dynamics:
M.L. Sambataro et al., *Eur.Phys.J.C* 80 (2020) 12, 1140

What is the underlying D_s?

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

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

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



*Main Differences in models:

- impact of **hadronization**
- **momentum depedence of diffusion**
- not all models describe data with the same quality [χ^2 and/or Bayesan analysis]

Future:

- Access **low p** & precision data (detector upgrade)
- Better insight into hadronization (Λ_c...)
- **New observables:** Extend to e-b-e: v_n , ESE q_2 selection & v_n(soft)-v_n(HQ) correlations + $v_1(y)$
  D-D triggered angular correlations
- Predictions & measurements for **B mesons**

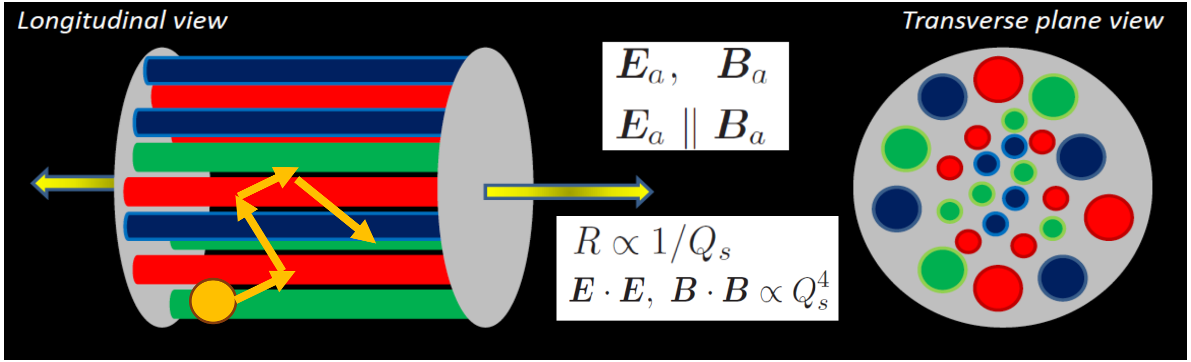
Reviews:

- F. Prino and R. Rapp, JPG(2019)
- X. Dong and VG, Prog. Part. Nucl. Phys. (2019)
- X. Dong, Y.J. Lee and R. Rapp, Ann.Rev.Nucl.Part.Sci. 69 (2019)
- Jiaxing Zhao et al., Prog. Part. Nucl. Phys. 114 (2020)

[Sambataro, Tue 10:30]

A first study of HQ in a Glasma

What happens for 0+<t<0.3-0.6 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)

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

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

Solving classical Yang-Mills

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

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

Solved in SU(2)

Heavy quark in the chromo magnetic field

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

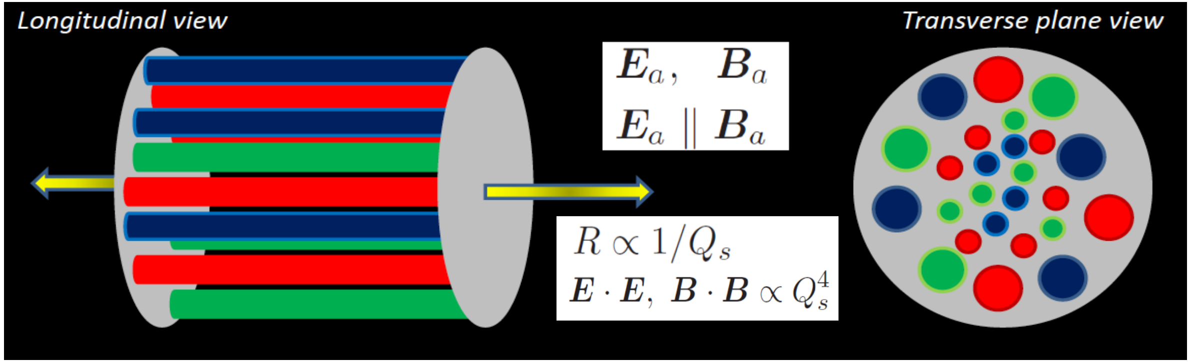
$$E\frac{dp_i}{dt} = Q_a F_{i\nu}^a p^\nu,$$

Wong's eq.

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

A first study of HQ in a Glasma

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



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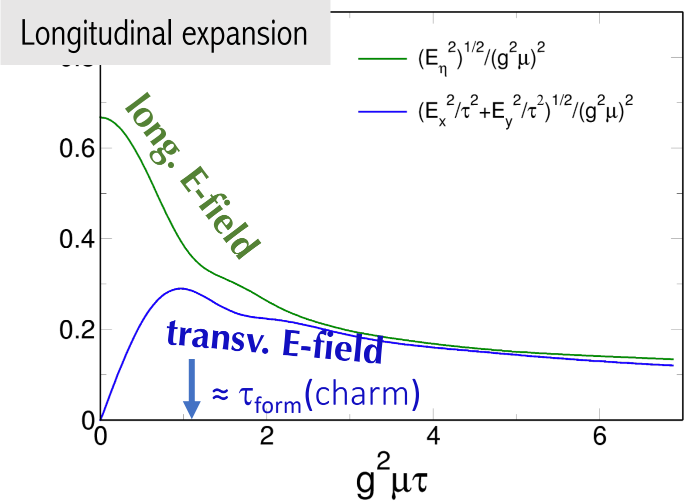
Longitudinal expansion



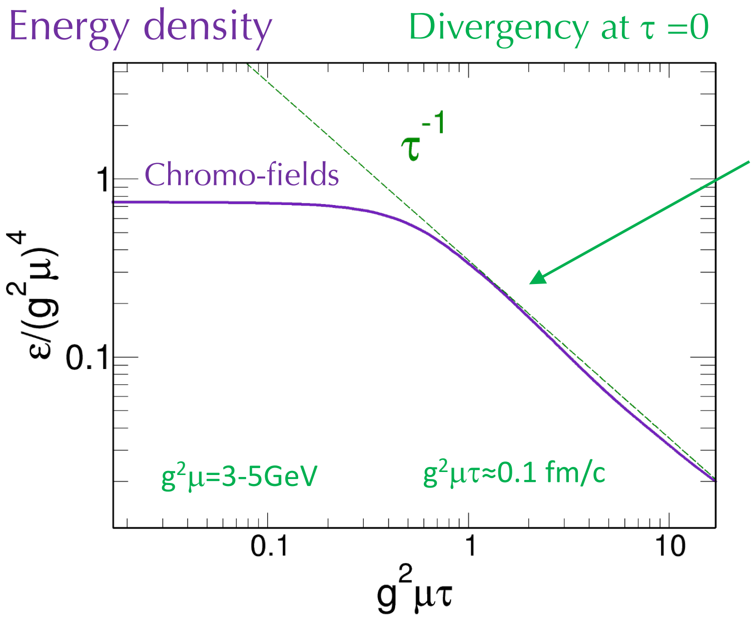
Formation time of transverse E-B fields $g^2\mu\tau \approx 1 \approx \tau_{form}$(charm)

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

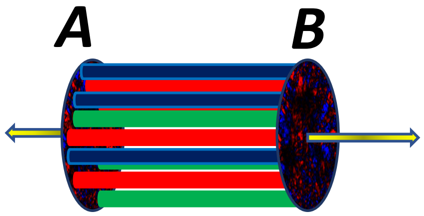
Initial State at t=0⁺ from chromo-magnetic fields



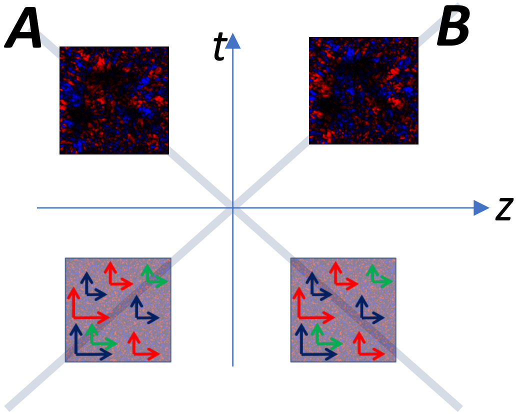
$$\frac{d\varepsilon}{\varepsilon} = -\frac{d\tau}{\tau}$$

description based on hydrodynamics or kinetic theory can start in this free streaming regime. [$\tau^{-4/3}$ ideal hydro]

$$\varepsilon = \frac{\varepsilon_0\, \tau_0}{\tau} \qquad \tau_0 \approx 0.3\text{-}0.6 \text{ fm/c}$$

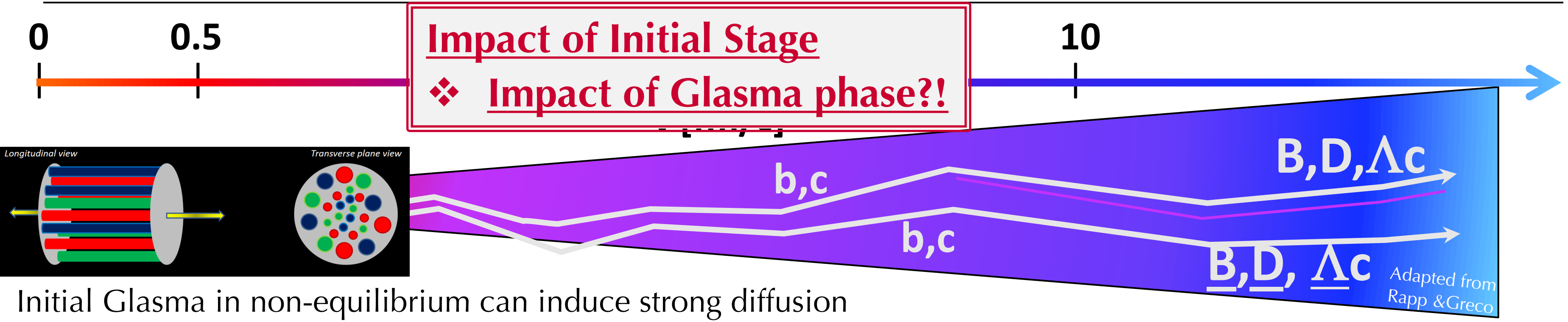


$$\nabla \cdot \boldsymbol{E} = ig\,[\mathcal{A}^i, \mathcal{E}^i]$$
$$\nabla \cdot \boldsymbol{B} = ig\,[\mathcal{A}^i, \mathcal{B}^i]$$



- Solving the t=0 divergency (≈ initio of the Collision Universe)
- The issue is not that the unknown early stage would destroy our current picture, but to find signatures of the early stage dynamics

Studying the HF in uRHIC

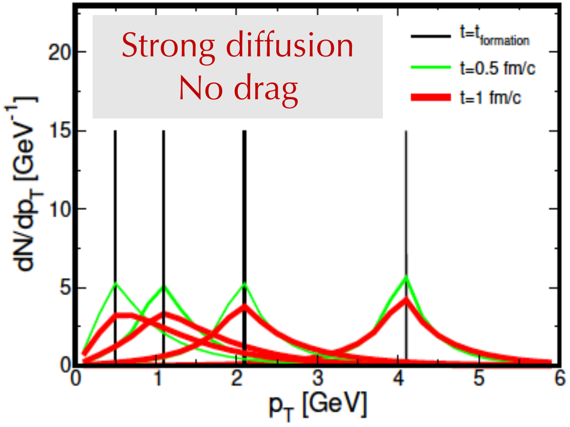


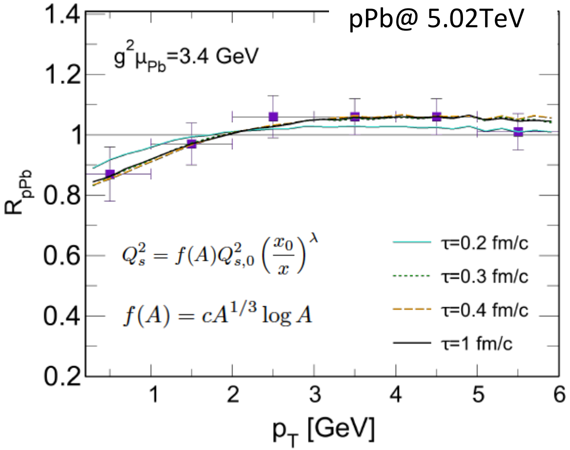
Initial Glasma in non-equilibrium can induce strong diffusion

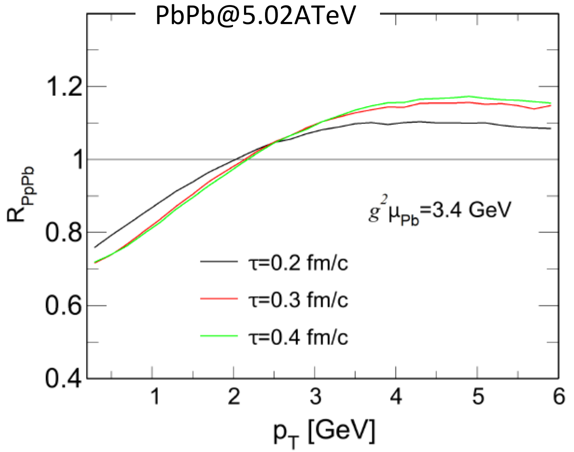
- M.Ruggieri and S.K. Das, PRD98 (2018)

First estimate of phenomenological impact

Static box- SU(2)

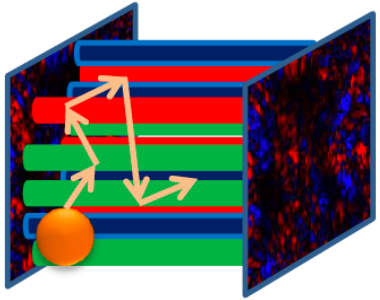




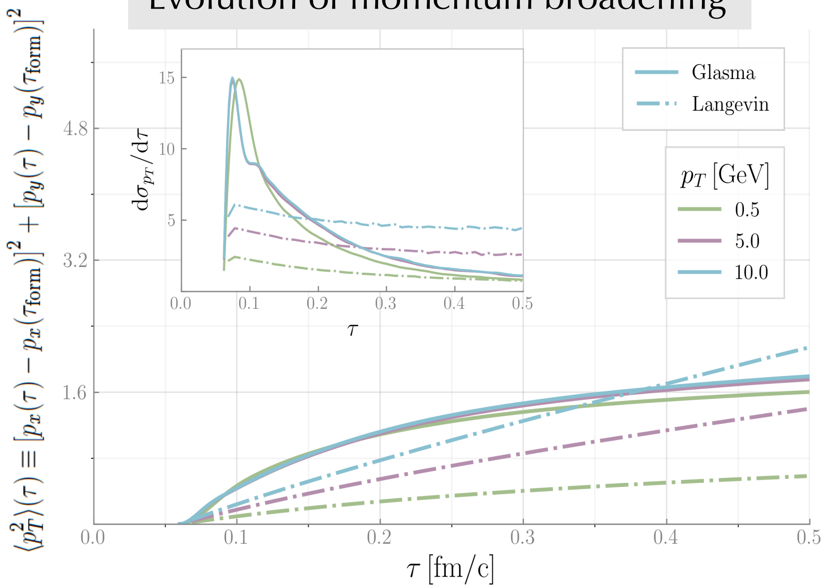


Comparison Glasma vs Langevin in early stage – SU(3)

Charm in the Glasma and Langevin starting at t_{form}=0.08 fm/c
Same underlying bulk energy density (central PbPb@5.02ATeV)
LV: Drag & Diffusion tuned to R_{AA}



Evolution of momentum broadening

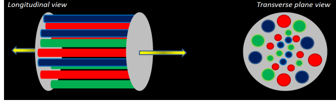


- Large initial broadening rate of Glasma at p_T < 5 GeV at $\tau \gtrsim 0.3$ fm/c LV (HQ scattering in QGP) becomes dominant
- Issue the transition from Glasma to QGP

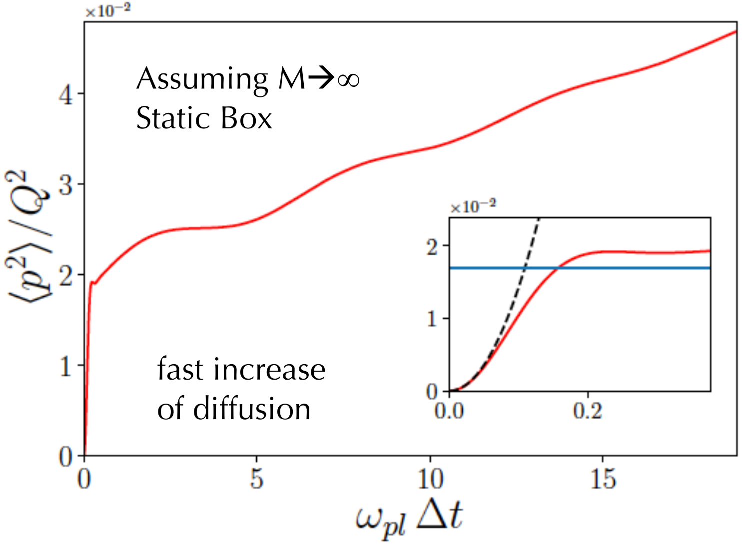
❖ To quantify the phenomenological impact start from FONNL and compare HQ Wong's in Glasma bulk vs LV in hydro bulk starting at $\tau_{form}=1/2m_Q$ and/or τ_0=0.3-0.6 fm/c

D. Avramescu et al., in preparation

Fast early diffusion (M→ ∞)



K. Boguslavski, A. Kurkela, T. Lappi and J. Peuron, JHEP09 (2020) 077   in SU(3) for M→ ∞



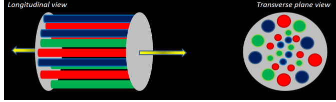
Correlator method

$$\langle \dot{p}_i(t)\dot{p}_i(t')\rangle = \frac{g^2}{2N_c}\langle E_i^a(t)E_i^a(t')\rangle$$

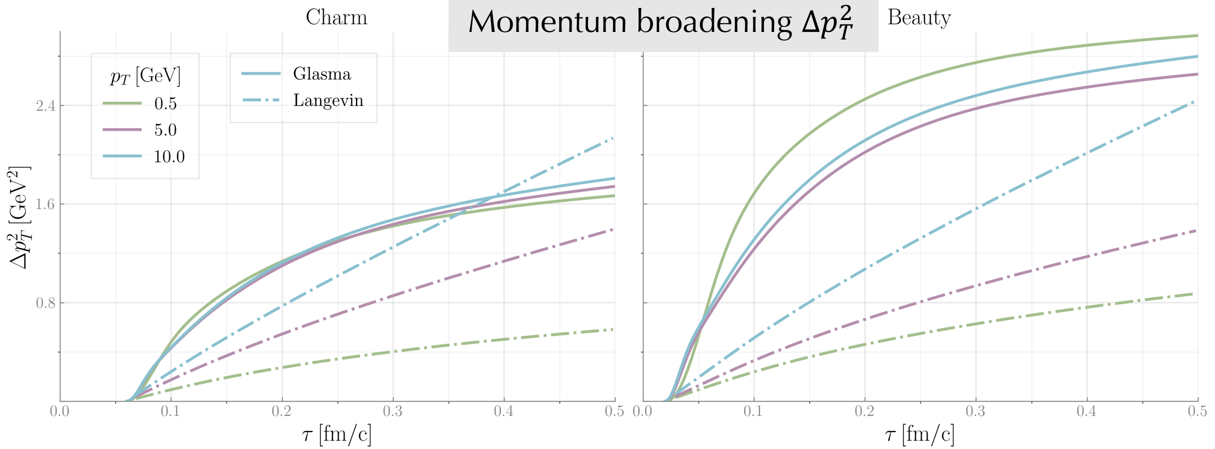
Not really a glasma, but an oveoccupied isotropic Gluon plasma:

Longitudinal and transverse E-field components at t_0

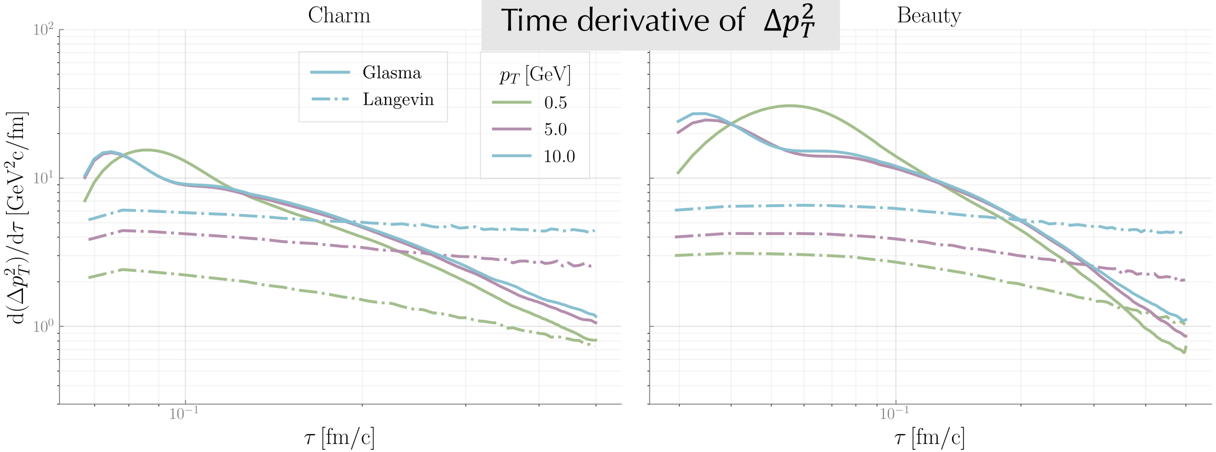
Mass effect: Charm vs Bottom in Glasma and LV



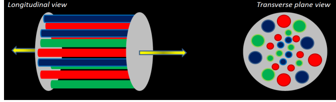
Momentum broadening Δp_T^2



Time derivative of Δp_T^2



Mass effect: Charm vs Bottom in Glasma and LV



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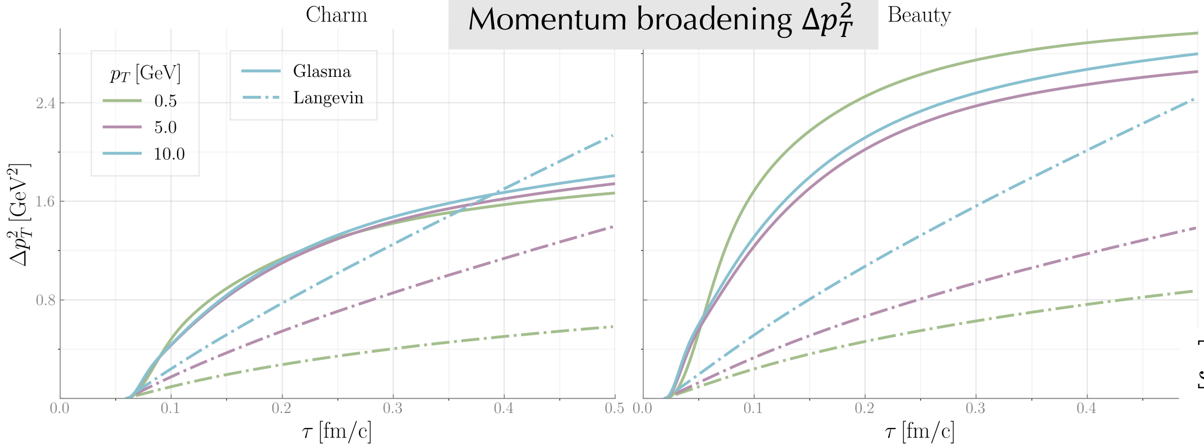
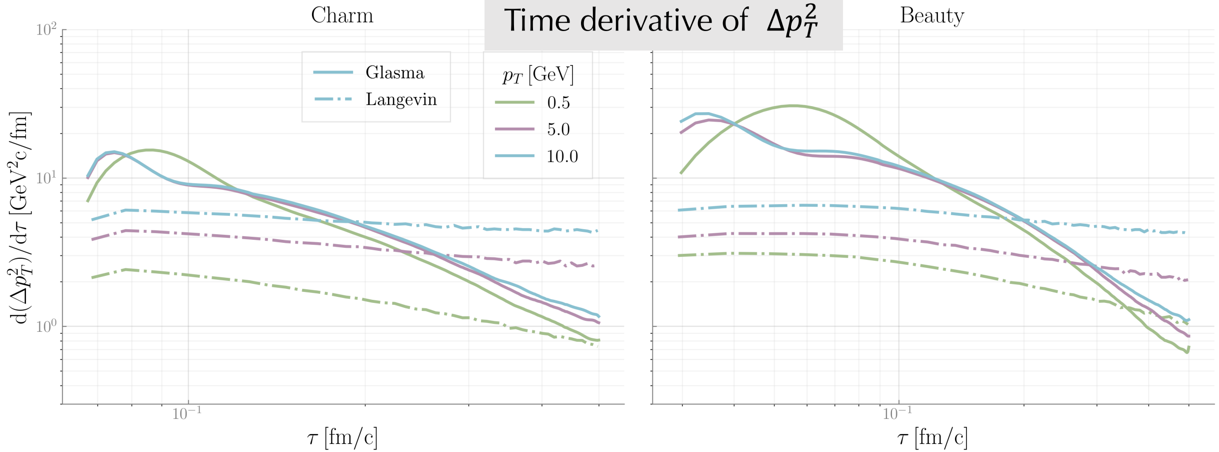
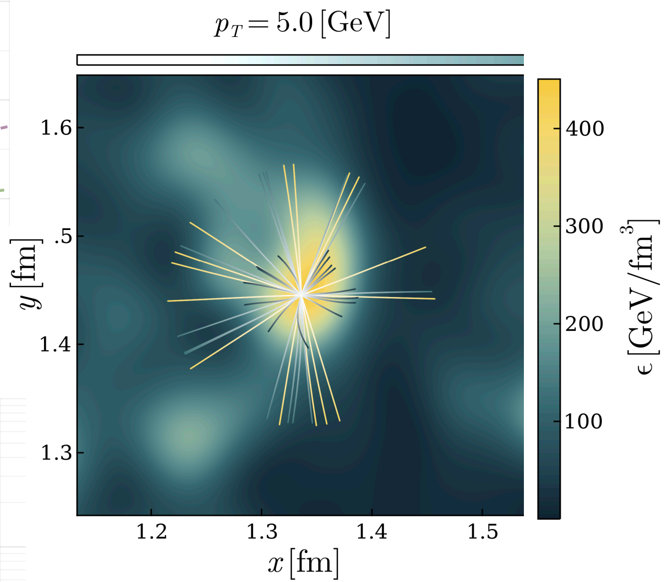


Time derivative of Δp_T^2

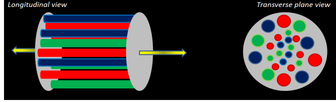


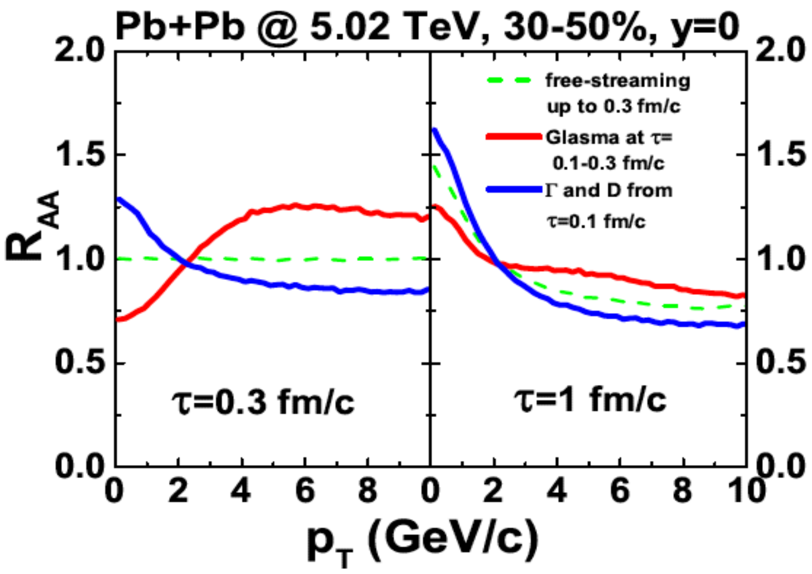
Large mass -> slower motion stays more in the correlated tube

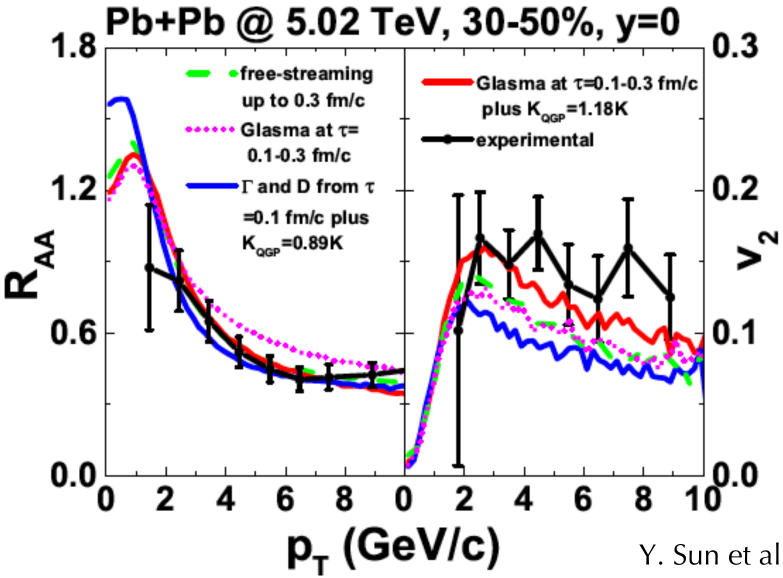


distribution so folding by it. The effective difference may be even smaller than for charm

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





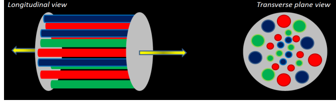


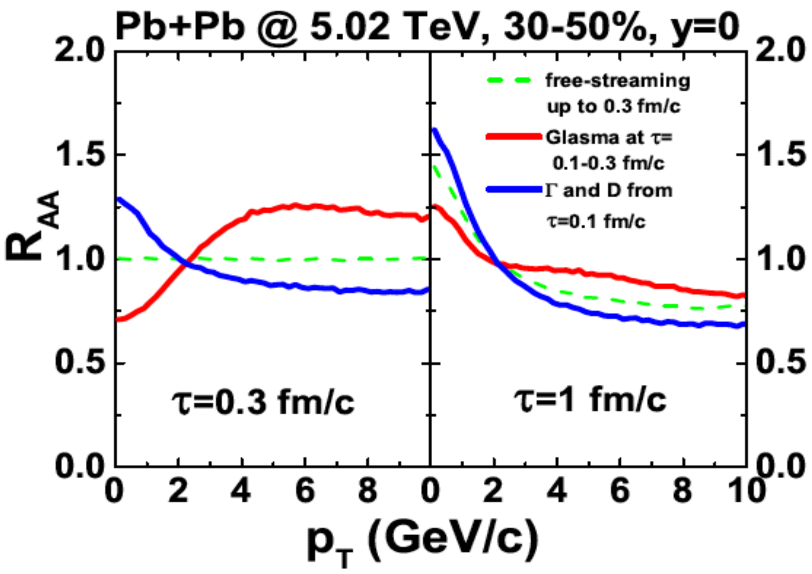
Y. Sun et al., PLB 798 (2019)

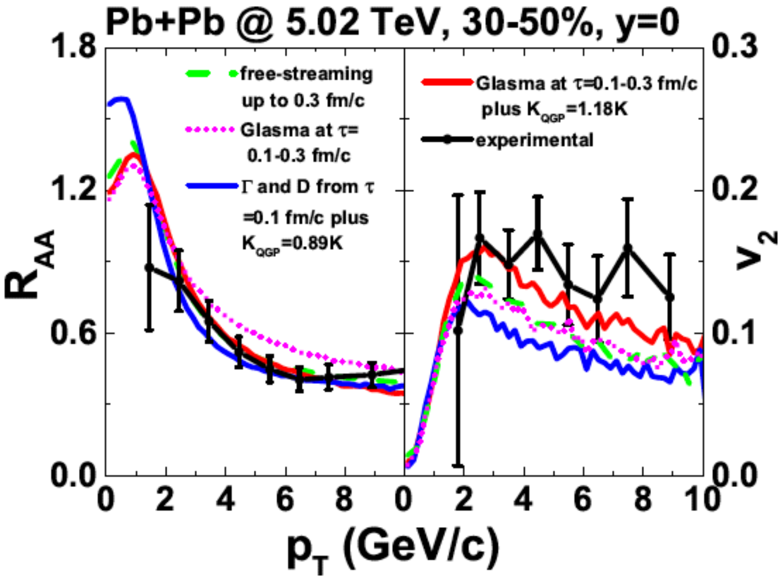
- Dominance of diffusion-like → initial **enhancement of $R_{AA}(p_T)$**
- **Gain in v_2**: larger interaction in QGP stage to have same $R_{AA}(p_T)$

To be done in SU(3) + smooth matching
+ early diffusion in realistic geometry (profile density)

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





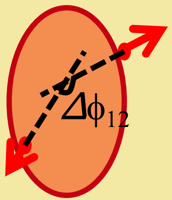


- Dominance of diffusion-like → initial **enhancement of $R_{AA}(p_T)$**
- **Gain in v_2**: larger interaction in QGP stage to have same $R_{AA}(p_T)$

To be done in SU(3) + smooth matching
+ early glasma diffusion in realistic geometry (profile density)

Link pA <-> AA

HQ as a probe of the Glasma
-> May have key role for
D-D̄ angular correlation



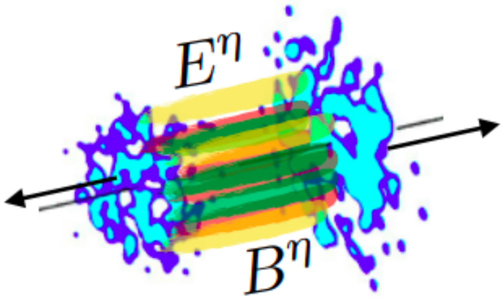
Motivation for HQ in the Glasma

- Role of HQ also in the CGC/Glasma studies

- Thorough study of HQ dynamics starting from $\tau_0 \approx 1/2m_Q \approx$ 0.02-0.08 fm/c

- Relevance to HQ in pA collisions (<->AA)
  - → may have a key role of D-$\underline{D}$ angular correlation

- May affect the determination of Ds(T)
  - → modify (improve) the relation R_{AA} & v_2

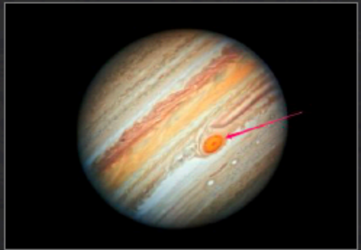


Strong fields in relativistic nuclear collisions

✓ HUGE ANGULAR MOMENTUM GENERATING A STRONG VORTICITY

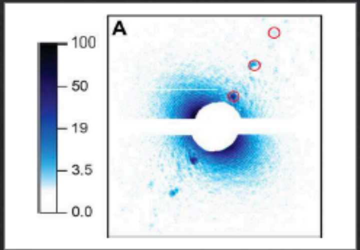
tornado cores

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



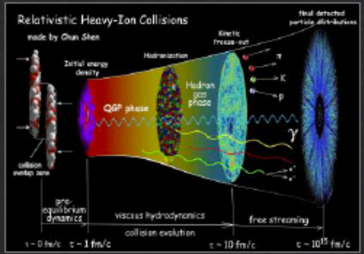
Jupiter's spot

$\sim 10^{-4}\ s^{-1}$



He nanodroplets

$\sim 10^{7}\ s^{-1}$



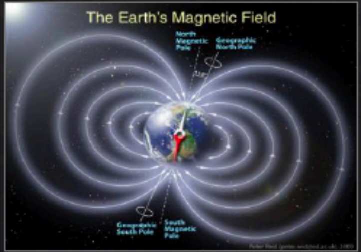
urHICs

$\sim \mathbf{10^{22}–10^{23}}\ s^{-1}$

vorticity

ω

✓ INTENSE ELECTROMAGNETIC FIELDS (EMF)



Earth's field

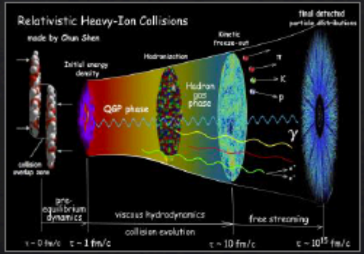
~ 1 G

laboratory

$\sim 10^{6}$ G

magnetars

$\sim 10^{14}–10^{15}$ G



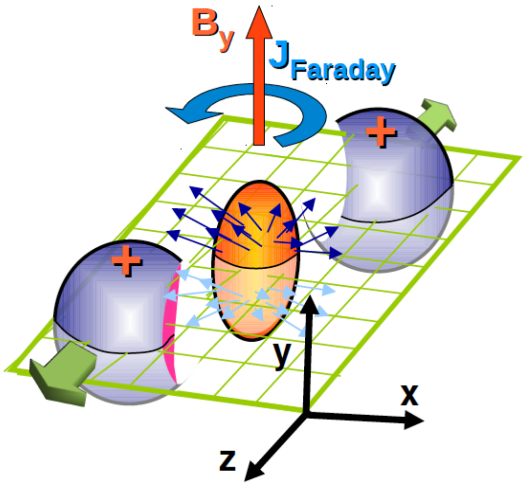
urHICs

$\sim \mathbf{10^{18}–10^{19}}$ **G**

magnetic field

B

Impact of large Electro-Magnetic Field in uRHICs



K Tuchin, Adv.High Energy Phys. 2013 (2013) 490495
K. Hattori, X.-G. Huang, arXiv:1609.00747 [nucl-th]

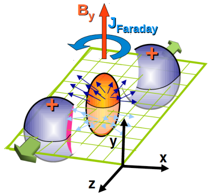
Strong B field induces:
- Chiral magnetic effect (CME)
- Chiral vortical effect (CVE)
- Hyperion polarization

C & *CP* local violation in Strong Interactions

Impacts on:
- Quarkonia states
- Radiative E_{loss}
- Electromagnetic radiation
- transport coefficients: viscosity, …

I will discuss only the direct classical effect of the e.m. field → splitting of charge/anti-charge collective flows

Electro-Magnetic field in HIC collisions



Start from point-like *Lienhard-Wiechart* retarded potentials (Biot-Savart law)

$$eB(t,\mathbf{r}) = \alpha_{em}\sum_a \frac{(1-v_a^2)(\mathbf{v}_a \times \mathbf{R}_a)}{R_a^3\left[1-(\mathbf{R}_a\times\mathbf{v}_a)^2/R_a^2\right]^{3/2}},$$

$$\left(\nabla^2 - \partial_t^2 - \sigma_{el}\,\partial_t\right)\boldsymbol{B} = -\nabla\times\boldsymbol{J}_{ext},$$

$$\left(\nabla^2 - \partial_t^2 - \sigma_{el}\,\partial_t\right)\boldsymbol{E} = -\nabla\rho_{ext} + \partial_t\boldsymbol{J}_{ext},$$

Fold them with the nuclear transverse density profile of the spectator nuclei and sum forward (+) and backward (-)

$$eB_{y,s} = -Z\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi' \int_{x_{in}(\phi')}^{x_{out}(\phi')} dx'_\perp x'_\perp \rho_-(x'_\perp) \times\left(eB_y^+(\tau,\eta,x_\perp,\phi) + eB_y^-(\tau,\eta,x_\perp,\phi)\right),$$

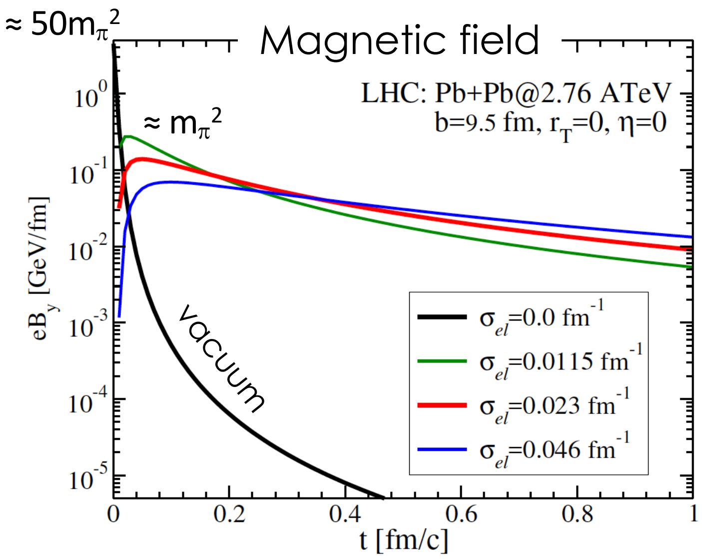
$$eE_x^+(\tau,\eta,x_\perp,\phi) = eB_y^+(\tau,\eta,x_\perp,\phi)\coth(Y_b-\eta)$$

Gursoy, Kharzeev, Rajagopal, PRC89(2014)

like in:

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

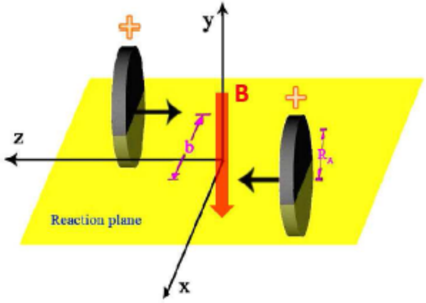
K. Tuchin, Adv. High Energy Phys. 2013, 1 (2013).



Assumptions:

- Medium at t<0
- Electric Conductivity const. in T → (r, t)
- No back reactions in the bulk due to currents
- No e-b-e fluctuations
- Neglected finite size of colliding nuclei

Impact of Magnetic Field on charged light hadrons



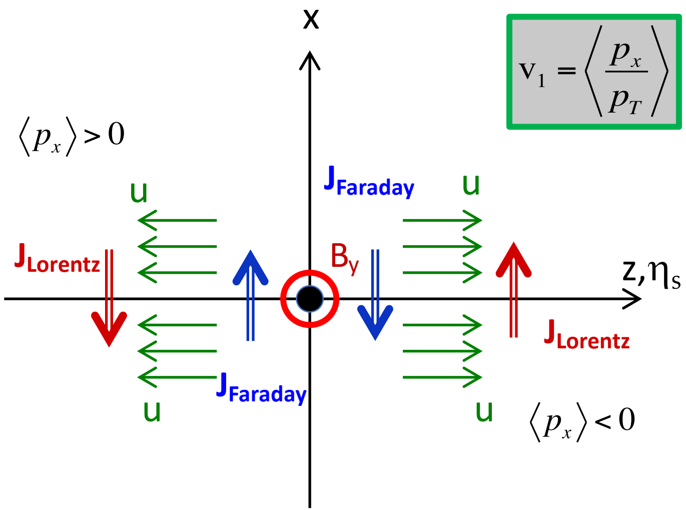
$$F_{ext} = q\mathbf{E} + \frac{q}{E_p}(\boldsymbol{p}\times\boldsymbol{B})$$

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

Faraday
[+ Coulomb spectators]

Lorentz

$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$



Gursoy, Kharzeev, Rajagopal, PRC89(2014)

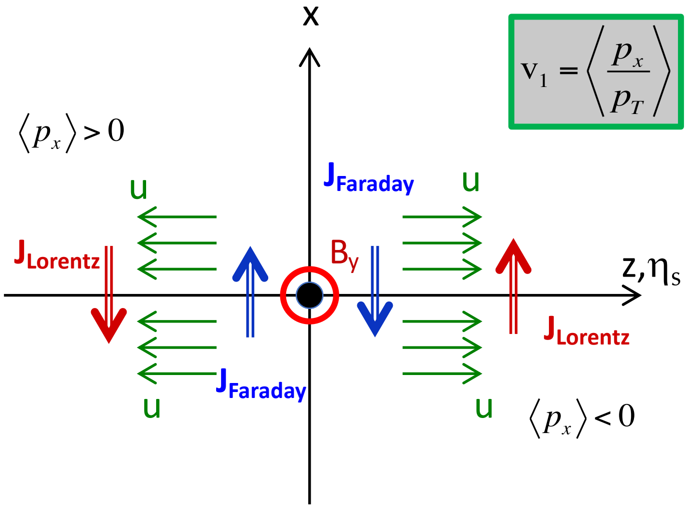
Impact of Magnetic Field on charged partons

$$\boldsymbol{F}_{ext} = q\mathbf{E} + \frac{q}{E_p}(\boldsymbol{p}\times\boldsymbol{B})$$

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

Faraday
[+ Coulomb spectators]

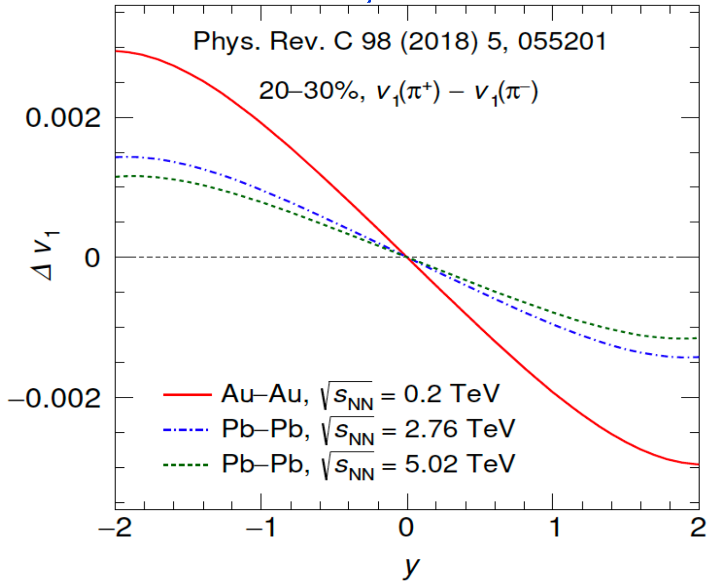
Lorentz



Gursoy, Kharzeev, Rajagopal, PRC89(2014)

Odd parity wrt charge ≠ v_1 vorticity

wins Faraday- Electric Field



STAR similar values – *opposite sign*

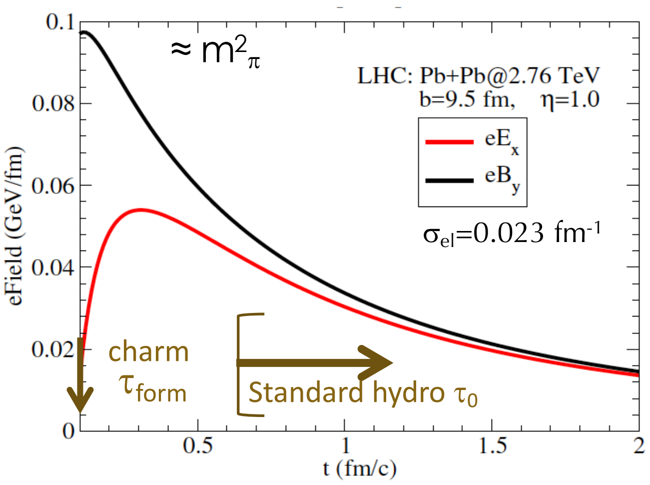
ALICE $d\Delta v_1/dy = (1.7 \pm 0.5 \pm 0.4)10^{-4}$ - *opposite sign*

* Delicate balance E and B fields

\+ small effects also from μ_B dependent mean fields

[C.M. Ko et al, PRL(2014)], Baryon transport into mid-rapidity

Impact of Magnetic Field on Charm



S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina, V. Greco, PLB**768** (2017) 260-264.

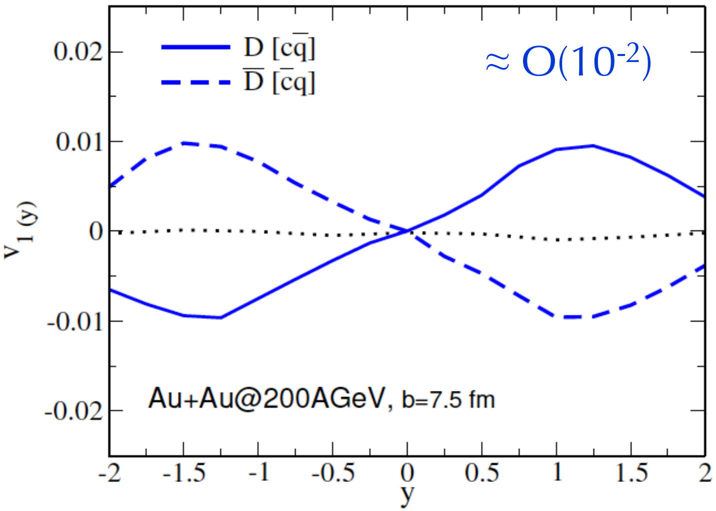
For charm quark we find a sizeable v_1

$\approx O(10^{-2}) \approx$ 10-50 times larger than π^+/π^-!

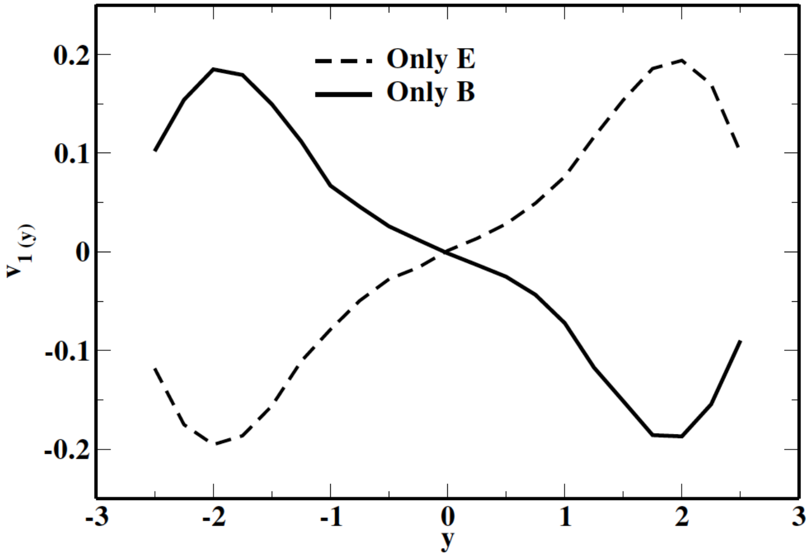
Using the same E-B field evolution as in U. Gursoy et al, PRC(2014)

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 $\pi^+/\pi^-, p/\bar{p}$
- $\tau_{th}(c) \approx \tau_{QGP} >> \tau_{e.m}$ (keep more memory effects)



Balance between Magnetic and Electric currents

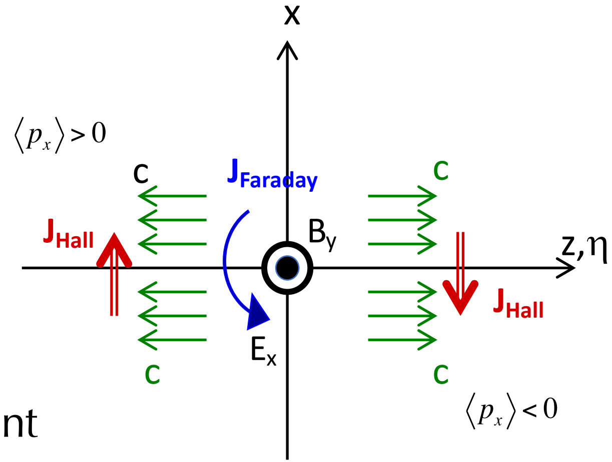


Simulation for charm quarks

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

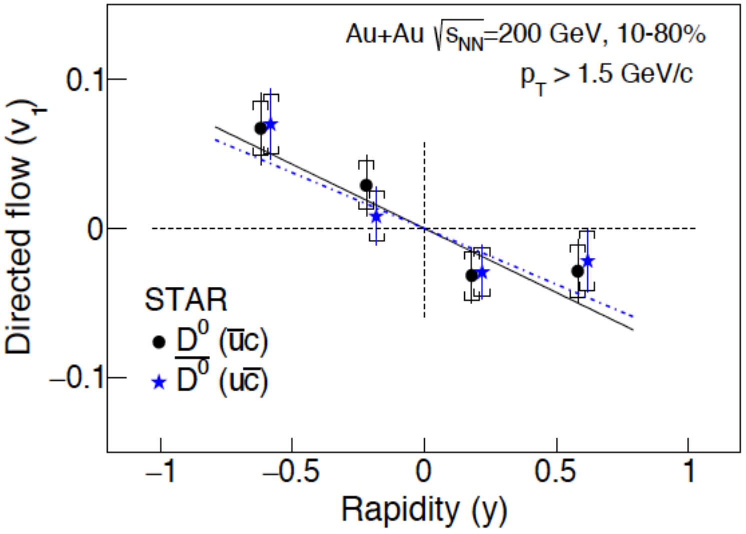
$$dp_i = -\Gamma p_i dt + \rho_i \sqrt{2Ddt} + q(E_i + \epsilon_{ijk} v_j B_k) dt,$$

Das et al., PLB768 (2017)



- ✧ Decreasing magnetic field B_y creates E_X that induces a current in opposite direction: delicate balance!

First Measurement of v_1 of D mesons



STAR, Phys.Rev.Lett. 123 (2019) 16, 162301

dv_1/dy=-0.080 ±0.017(stat)±0.016(syst)

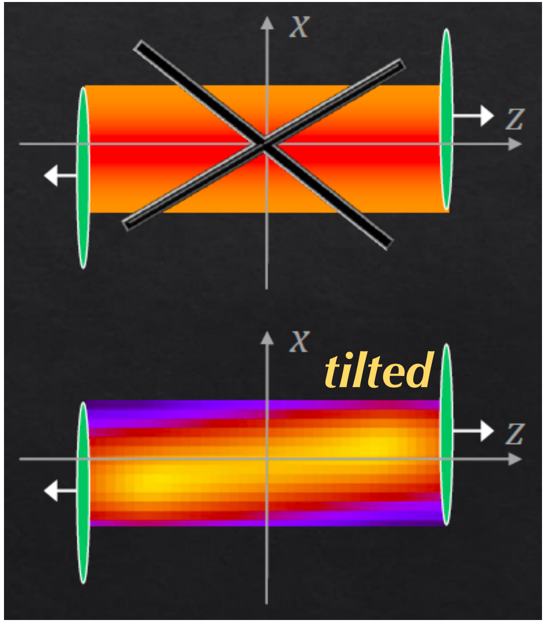
Huge v_1 about **30 times larger** than the kaon one

Excellent qualitative prediction of
Chatherjee and Bozek, PRL 120 (2018)
$dv_1/dy \approx$ 0.02-0.04 ($\approx$ 10-15 times larger than light-charged)

Very surprising that v_1 heavy quark >> v_1 light quarks

v_1 of D mesons: quantitative study

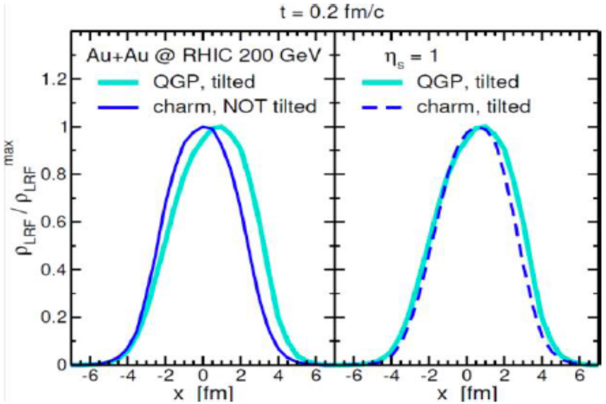
Oliva, Plumari, V.G., JHEP05 (2021) 034



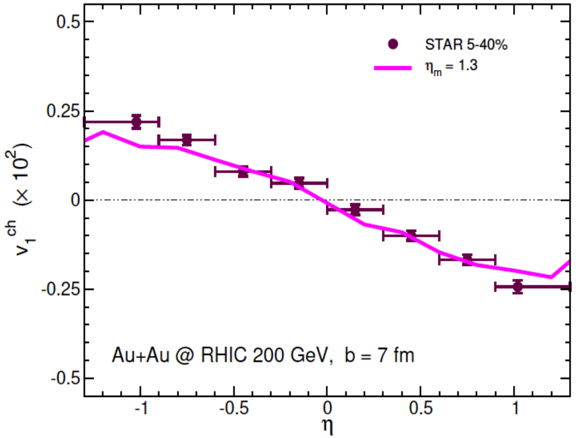
$$W(x_\perp, \eta_s) = 2\,(N_A(x_\perp) f_-(\eta_s) + N_B(x_\perp) f_+(\eta_s))$$

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

P. Bozek and I. Wyskiel, PRC 81(2010) 054902



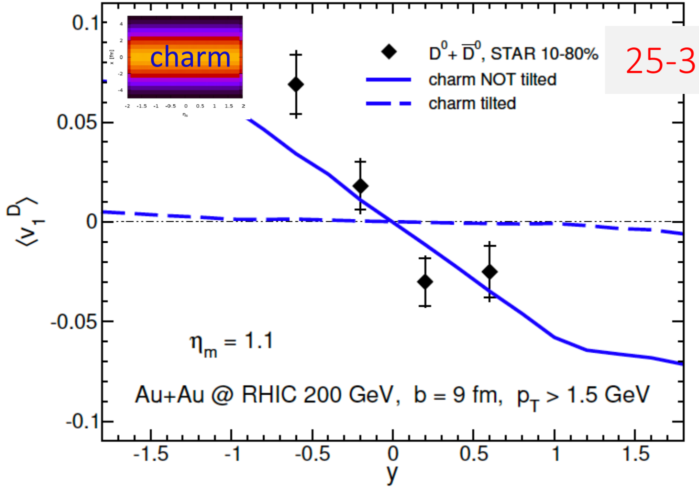
"Tilt" fix bulk v_1



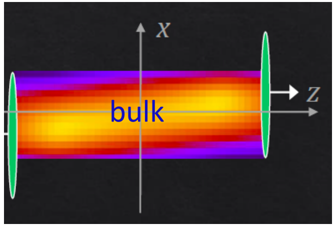
Quantitative good description v_1 of D mesons

Oliva, Plumari, V.G., JHEP05 (2021)

Needed initial "tilt" of bulk and no of HQ



25-30 times larger than **charged**



dv_1/dy=-0.080 ±0.017(stat)±0.016(syst)

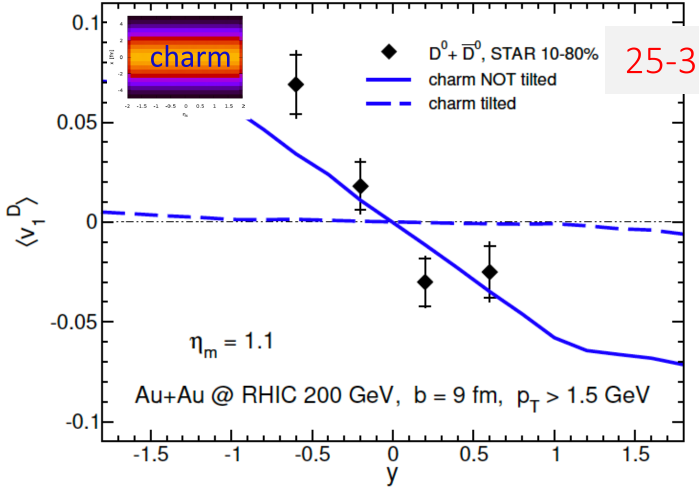
dv_1/dy = - 0.065 (theory)

v_1 of D mesons probe 3D bulk + non-pertubative

Oliva, Plumari, V.G., JHEP05 (2021)

Needed initial “tilt” of bulk and no of HQ

Needed non-perturbative HQ interaction



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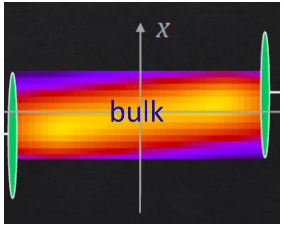
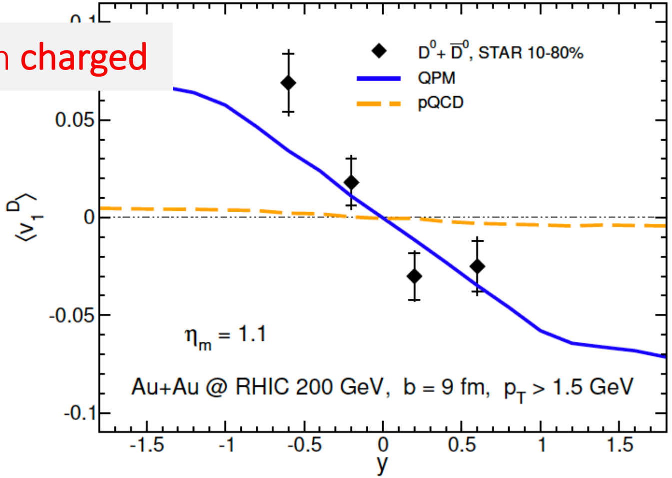
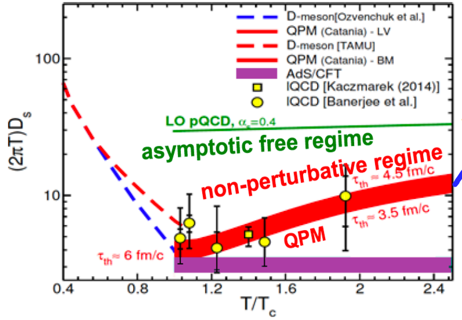




$dv_1/dy = -0.080 \pm 0.017(stat) \pm 0.016(syst)$

$dv_1/dy = - 0.065$ (theory)

$D_s(T)$-QPM from R_{AA} and v_2



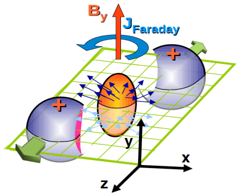
Same charm interaction $D_s(T)$ to reproduce $R_{AA}(p_T)$and $v_2(p_T)$

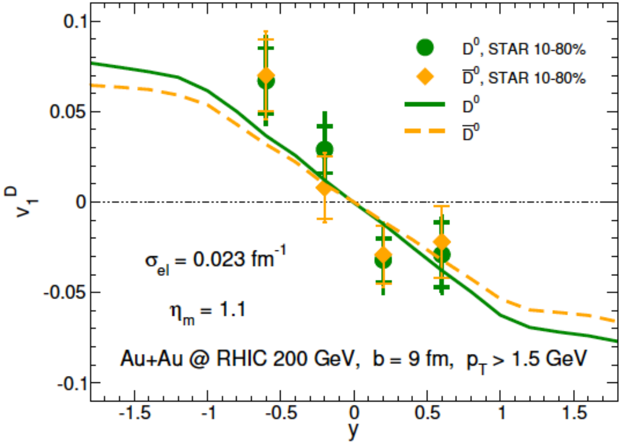
\+ vorticity and J_y employed for Λ polarization

\+ v_1 of light particles: quite a self-consistent description ☺

Δv_1 from e.m. field?

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

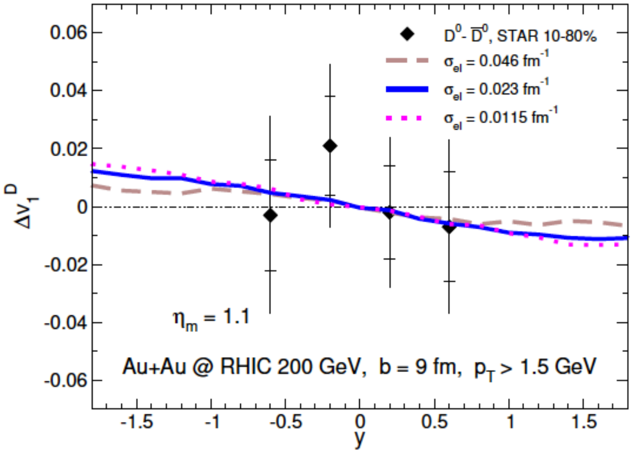




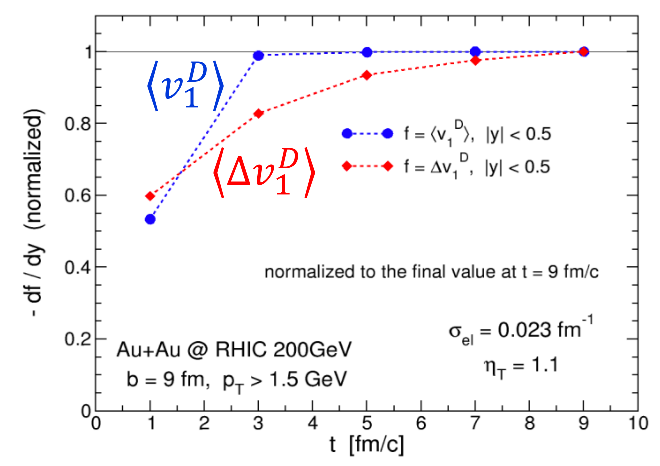
$d(\Delta v_1)/dy|_{exp} = -0.011 \pm 0.024(stat) \pm 0.016(syst)$

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

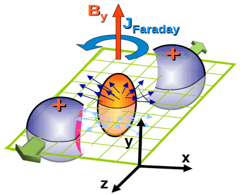


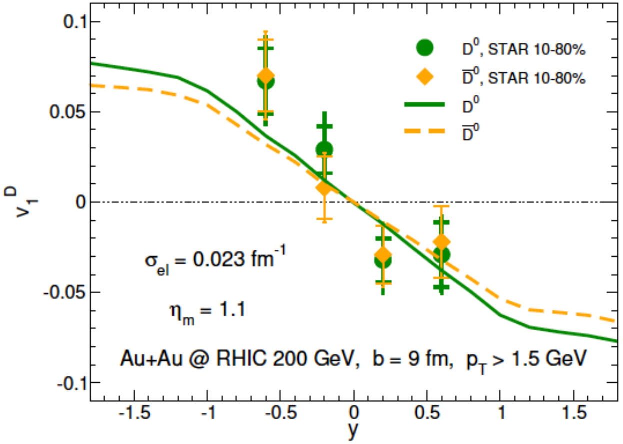
v_1 expected to be more sensitive than v_2 to high T (early time) $D_s(T)$!

Unexplored…

Δv_1 from e.m. field?

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





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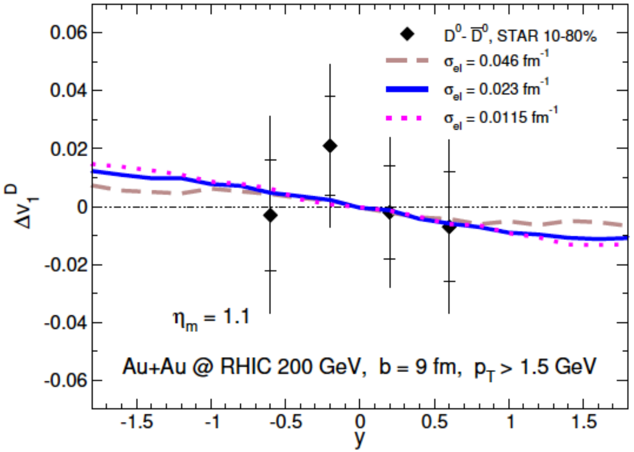
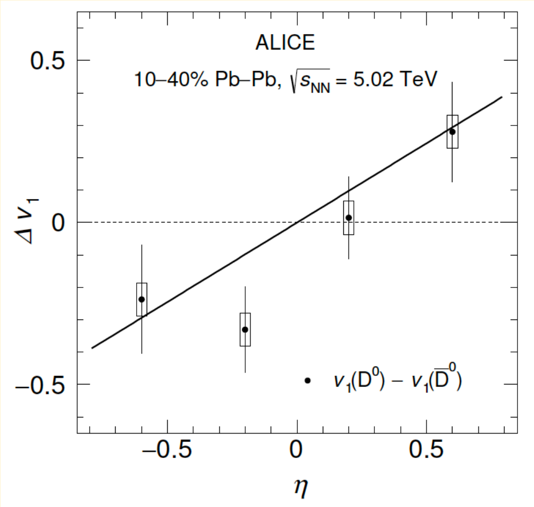
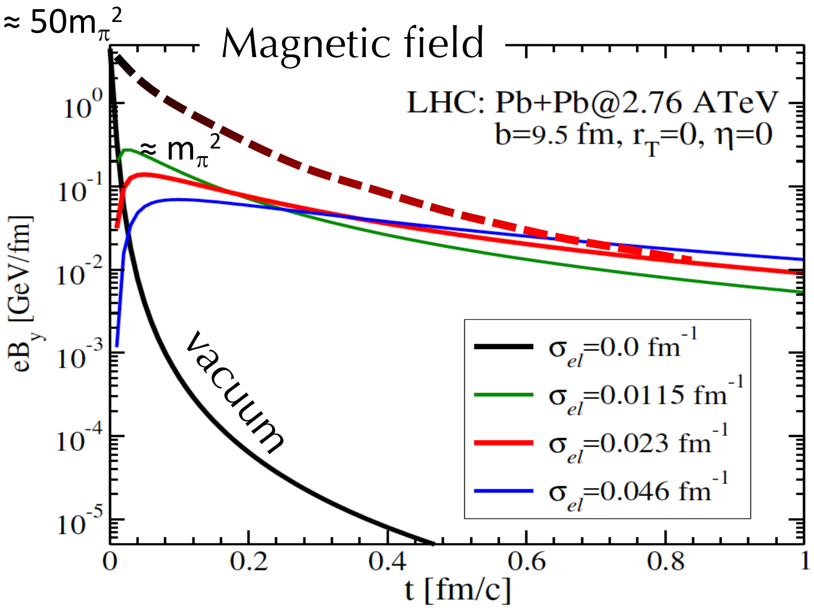


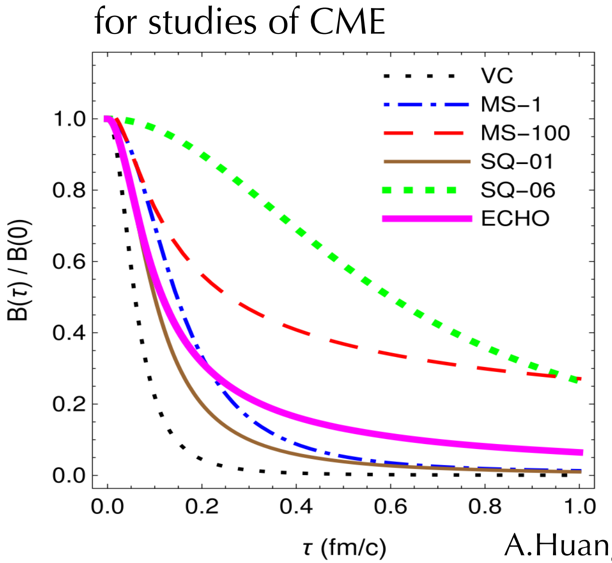


$d(\Delta v_1)/dy$ for D^0 50 times larger RHIC
$d(\Delta v_1)/dy \approx 10^{-4}$ for charged particles

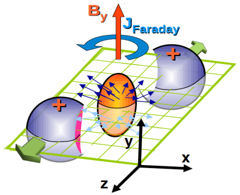
Opposite sign & magnitude
≈ 40 times larger than model predictions
Δv_1 (RHIC) ≈ Δv_1 (LHC)
What's going on?

Electro-Magnetic field is not really under control





A.Huang et al., PLB777(2018)



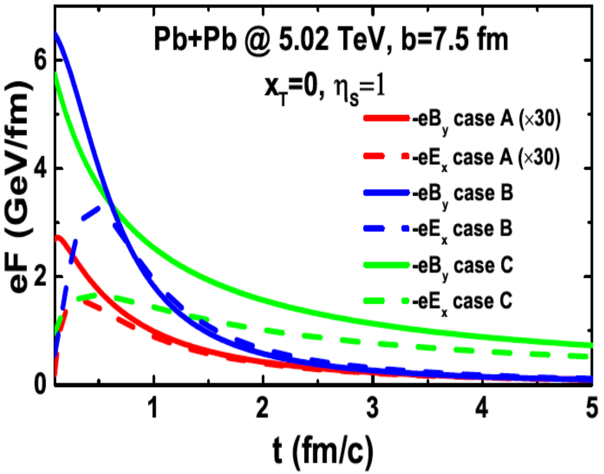
Computation of early stage e.m. field is quite an issue:

- **large gap @LHC:** $eB_y(t=0)$ in the **vacuum:** $\approx 50\ m_\pi^2$ but $eB_y(t=0)=0$ assumimg a **medium** in equilibrium at σ_{el}

  → $\sigma_{el}(t)$ for t <1 fm/c and then $\sigma_{el}(T)$ as lQCD ?

- NOTE: In the medium (t<0) σ_{el}=const. approach the magnetic field at RHIC and LHC are essentially equal!
- Early time what is σ_{el} in the Glasma + more exotics: Chiral topological charge [arXiv:2002.05047,Tuchin] etc..

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 $\sigma_{el}=0.023$ fm^{-1}

Case B and C [B_0 at t=0 vacuum value]

$$eB_y(x,y,\tau) = -B(\tau)\rho_B(x,y) \quad \tau_B=0.4 \text{ fm/c}$$

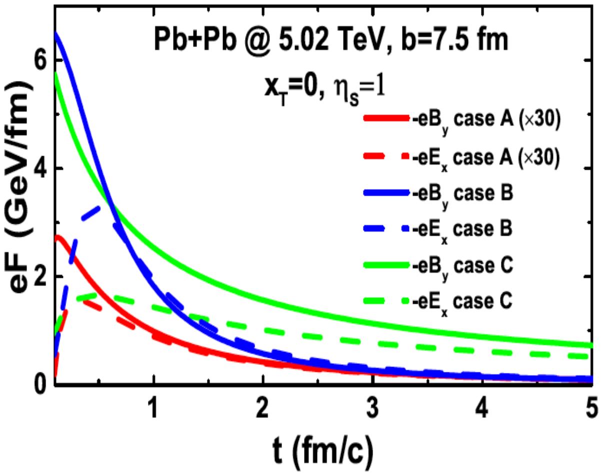
$$B(\tau) = eB_0/(1+\tau^2/\tau_B^2)$$

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

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

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

E.m. field: a main source of uncertainty



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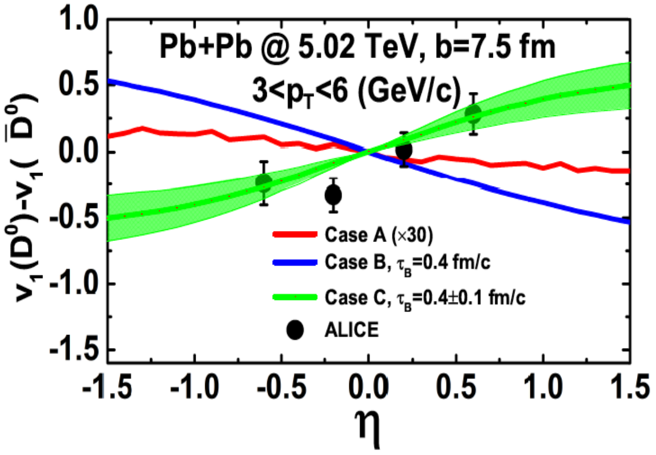
$$B(\tau) = eB_0/(1+\tau/\tau_B)$$

$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$: 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, $\mathbf{E_x \approx 0.5\, B_y}$ (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?

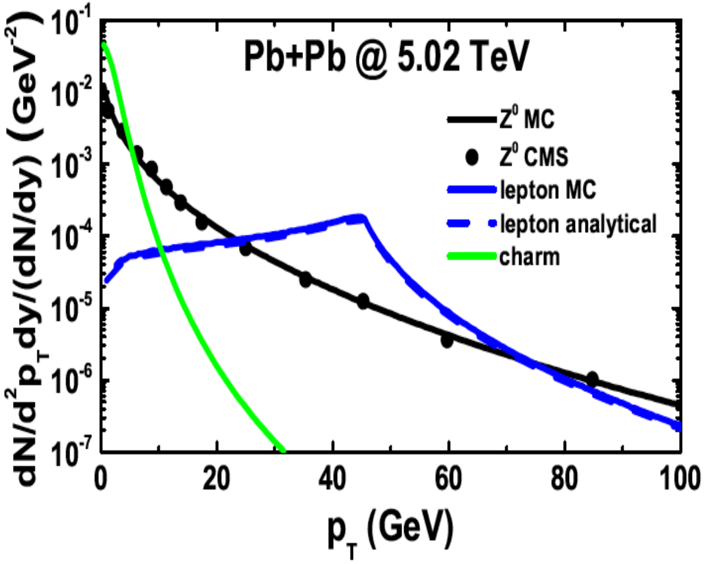
Is there a further way to pin down the e.m field strength?

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

Leptons from Z^0?

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



What one expects?

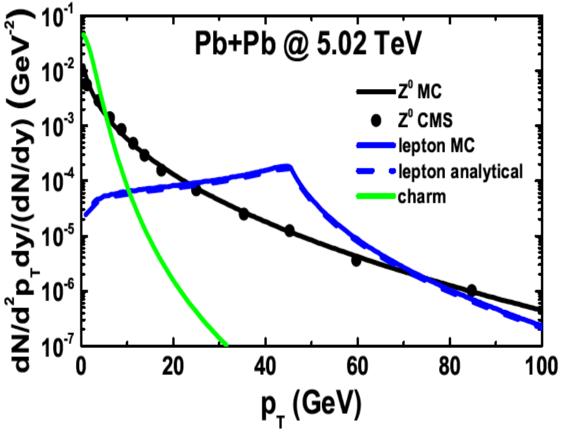
- No damping from medium interaction
- Massless more easily to drag
- Charge 1.5 times larger

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

– **$\tau_{decay}(Z^0)= \tau_{form}$(charm)=0.08 fm/c: they go through the e.m. fields at the same time**

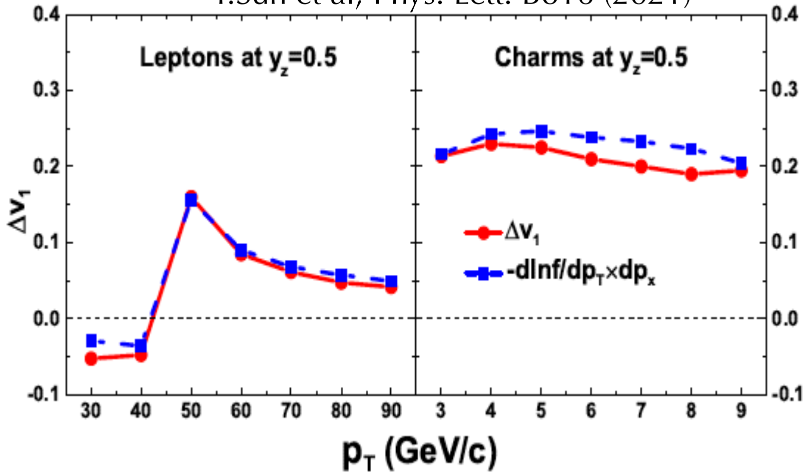
→ meanfigul look at the correlation $\Delta v_1(D^0,\underline{D}^0)$ and $\Delta v_1(l^+,l^-)$

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)



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

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

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 $\Delta v_1(D^0)$?

What determines the Δv_1?

Why leptons from Z^0 should be quite correlated to D-$\underline{D}$?

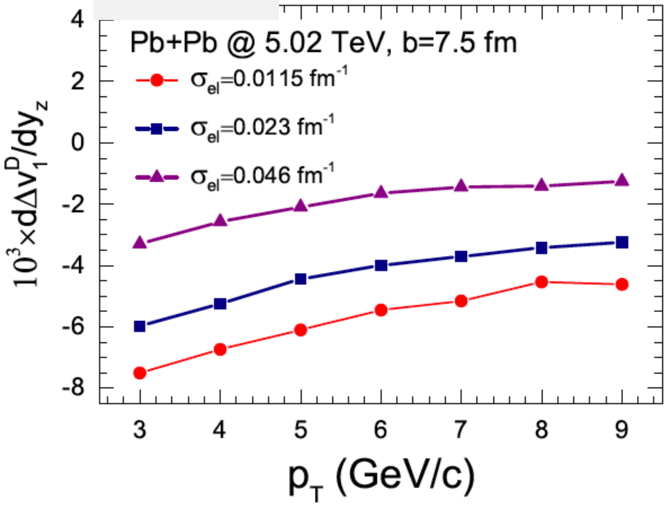
- Large By at t=0? Its time derivative? p_T spectrum? Mass charm vs bottom? …

An undergoing first tentative to get more insight…

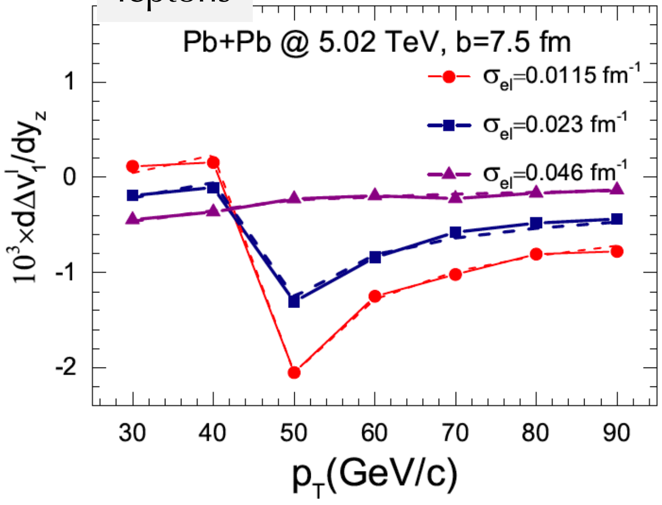
Relation Δv_1 of D^0 and leptons from Z^0: σ_{el} const.

Y. Sun, S. Plumari, VG, EPJ Plus 136 (2021)

D meson



leptons



Approximate analitical formula

$$\frac{d\Delta v_1^c}{dy_z}\Big|_{y_z=0} = -\alpha\frac{\partial \ln f_c}{\partial p_T} + (2\alpha - \beta)\frac{p_T}{m_T^2}$$

$$\alpha = |q|K\left[\tau_1 B_y(\tau_1) - \tau_o B_y(\tau_0)\right]$$

- discarding medium interaction
- assuming an elliptic "rigid" bulk
- slow variation of E-B in the transverse plane

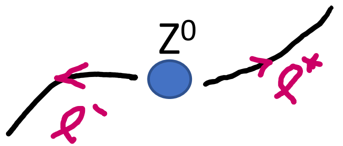
$\Delta[tB_y(t)]$ is the quantity driving the splitting Δv_1

It includes the balance with the electric field under $\frac{\partial E_z}{\partial x} \approx 0$ asumption

Peak disappears only if $\alpha \approx 0$, which happens with $\Delta v_1 \rightarrow 0$ (10^{-3})

The correlation between the D^0 & Z^0 supply an info on the e.m. origin

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



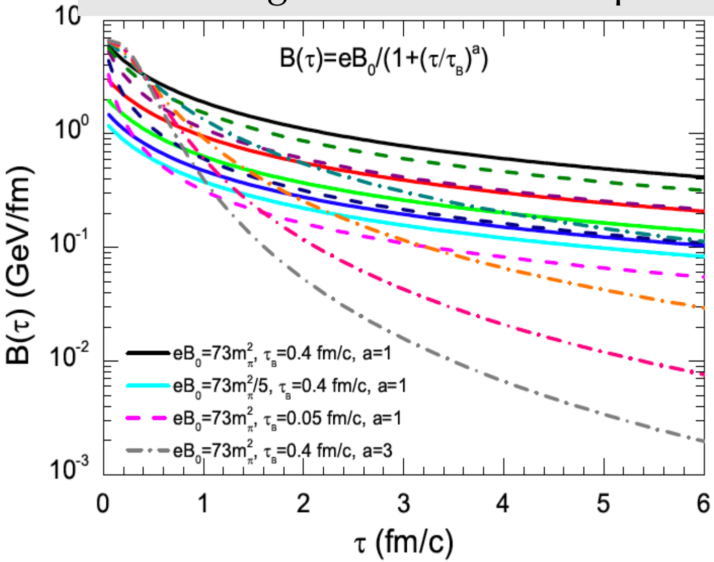
Acquire **Δp** by e.m field
-> modify invariant mass

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

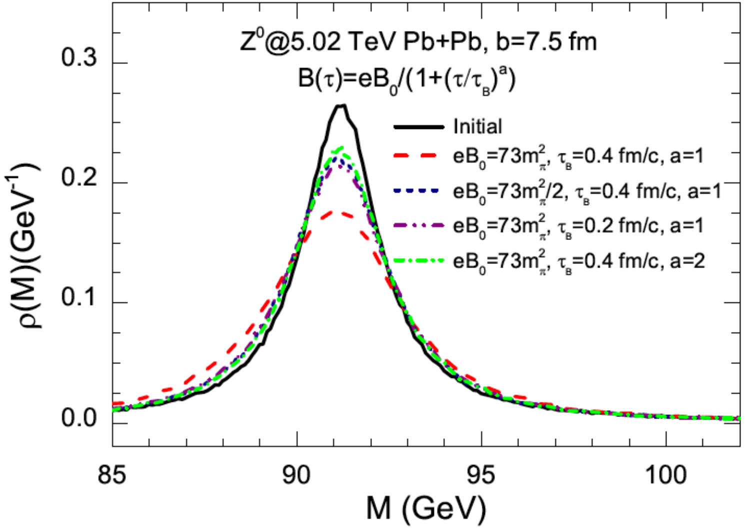
- Mass peak decrease
- Γ width increase

Y.Sun, V. Greco, X.N. Wang, arXiV:2111.01716 [37]

Wide range of B(τ) different pattern

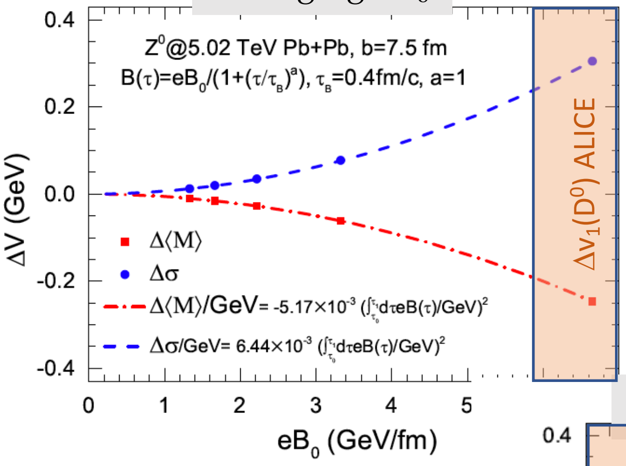


Invariant mass distribution o l^+l^-

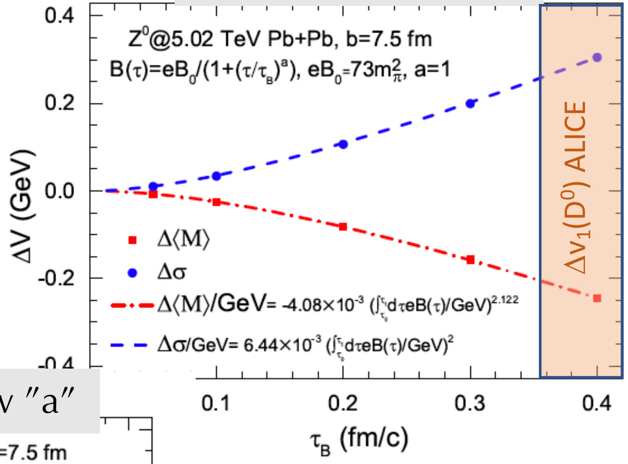


Z^0 mass and width modification in AA

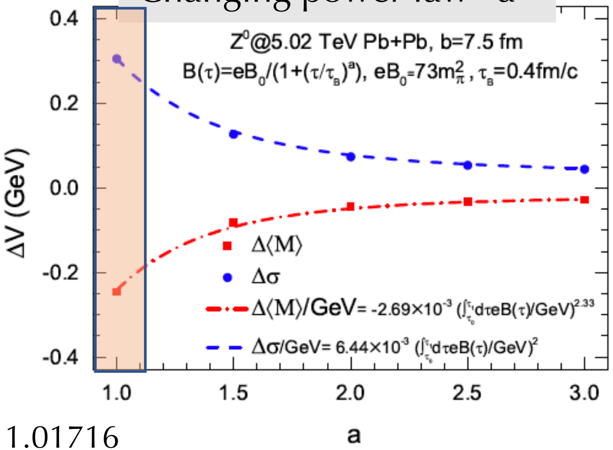
Changing eB_0



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

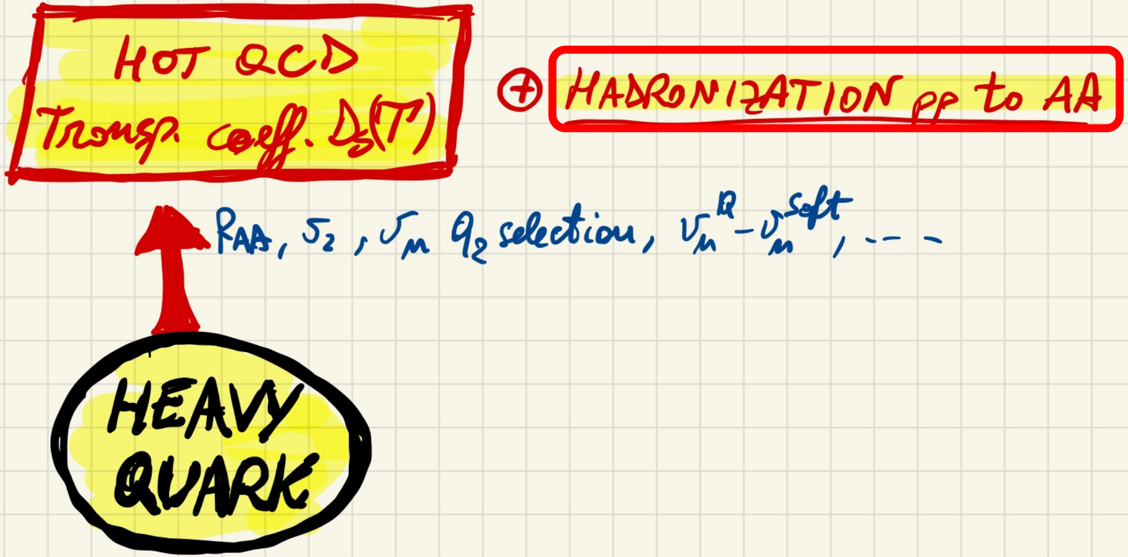
To be done vs centralities, systems,…

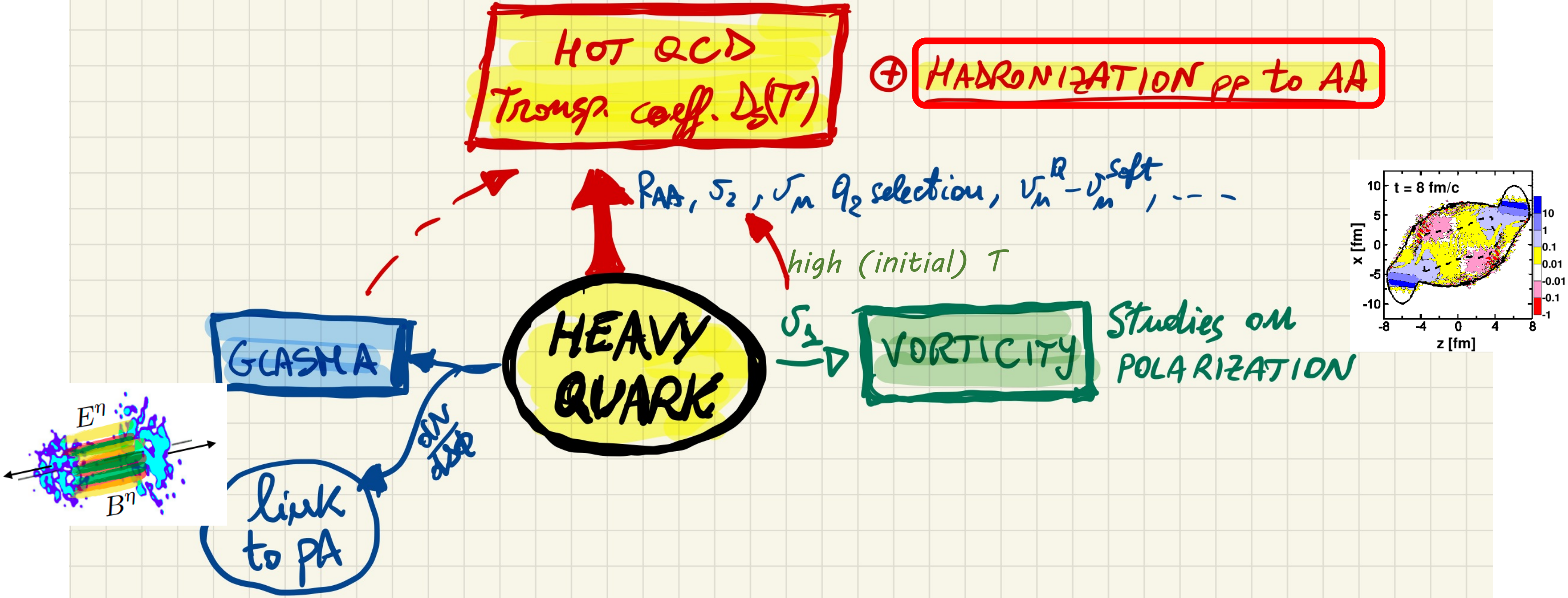
Conclusions & Perspectives

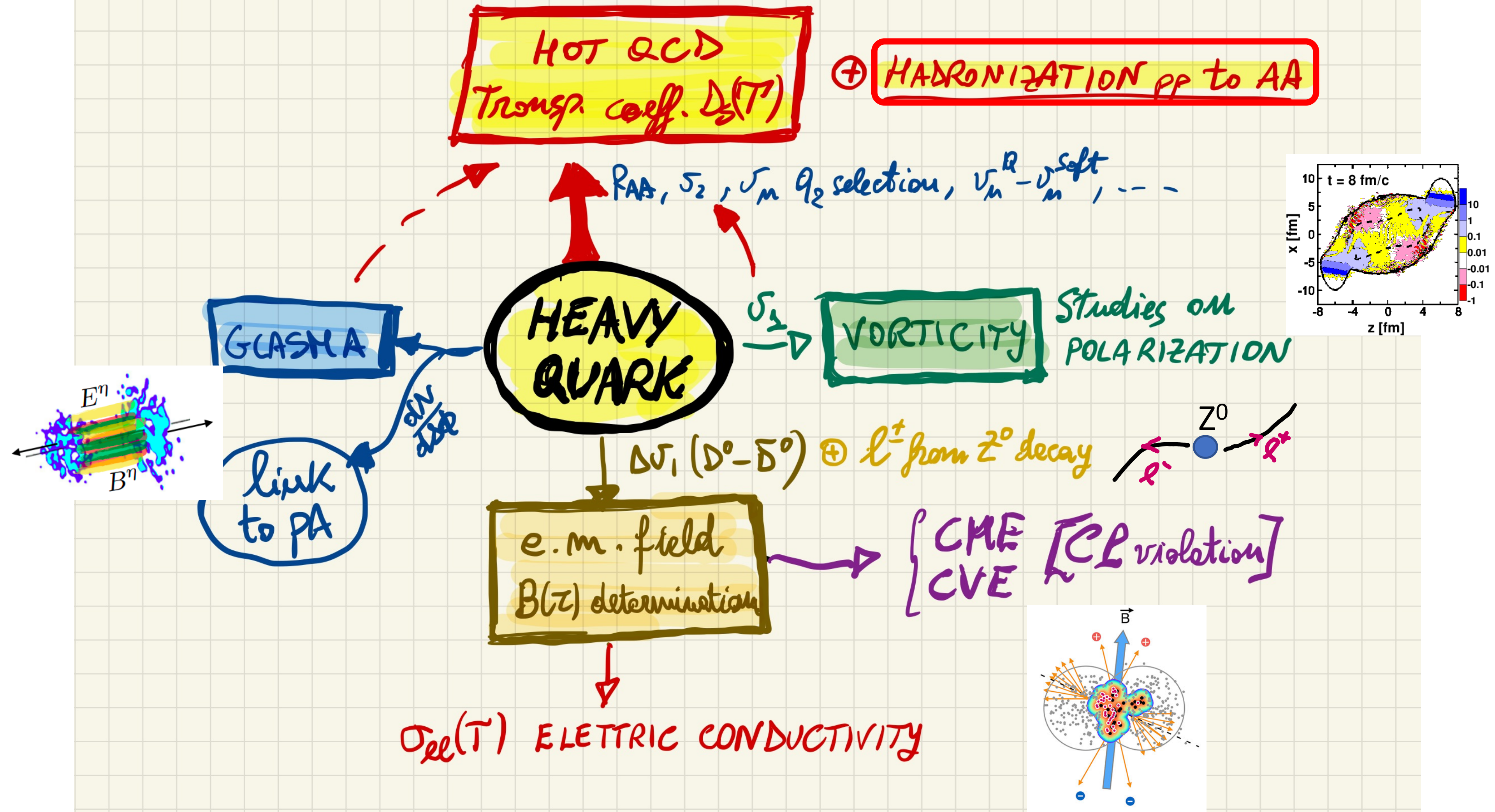
- Estimate of $D_s(T)$ [non –perturbative ≈ AdS/CFT] from R_{AA} & v_2 successful:
  - v_1 should be added to efforts for $D_s(T)$: more sensitive to high (initial) T
  - * Glasma impact: link pA and AA

- **Charm ΔV_1 can allow to access the initial strong E-B field and vorticity :**
  - * splitting in $\Delta v_1(l^+, l^-)$ from Z^0 decay can clarify the e.m. origin of $\Delta v_1(D^0 - \overline{D}^0)$@LHC
  - * Bottom can supply info on the evolution of $B_y(t)$ at earlier t≈0.03fm/c (B_y→0 or B_y→ vacuum)

> - if $\Delta v_1(D^0 - \overline{D}^0)$ has an e.m. origin→ **probe of deconfinement vs flavor**
> - constraint on e.m. field → **quantitative studies of CME, CWE, CMW, hyperon polarization**


HOT QCD
Transp. coeff. $D_s(T)$
⊕ HADRONIZATION pp to AA
R_{AA}, v_2, v_n q_2 selection, $v_n^Q - v_n^{soft}$, ---
HEAVY QUARK

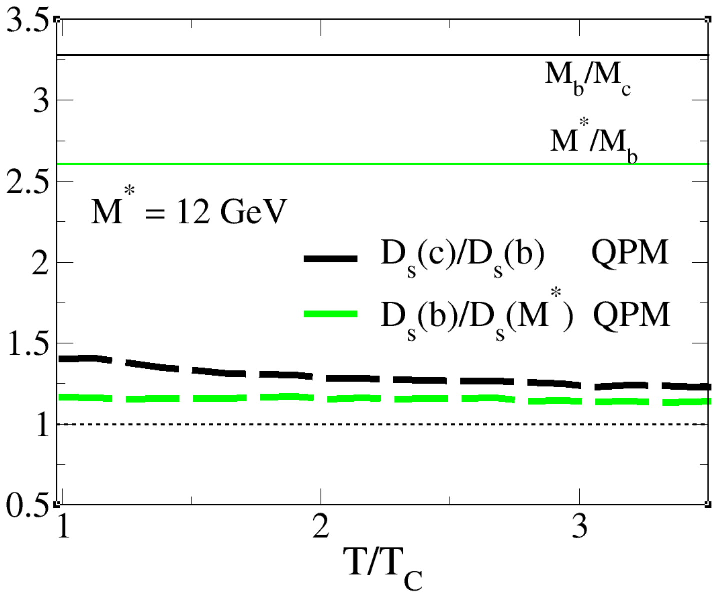

HOT QCD
Transp. coeff. $D_s(T)$
⊕ HADRONIZATION pp to AA
R_{AA}, v_2, v_n q_2 selection, $v_n^Q - v_n^{soft}$, - - -
high (initial) T
HEAVY QUARK
GLASMA
E^η
B^η
link to pA
$\frac{dN}{d^2p}$
v_1
VORTICITY
Studies on POLARIZATION
t = 8 fm/c
x [fm]
z [fm]



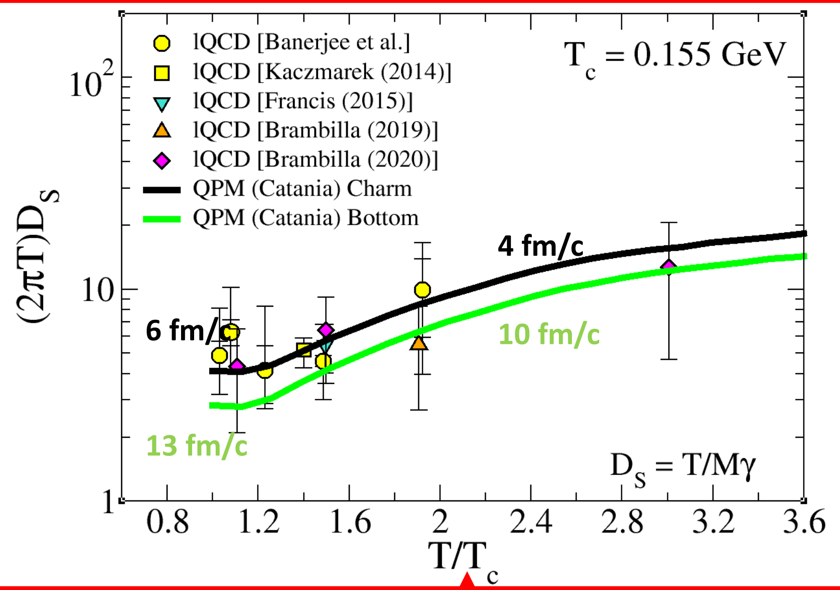
HOT QCD
Transp. coeff. Ds(T)
⊕ HADRONIZATION pp to AA
RAA, v2, vn q2 selection, vn^Q − vn^soft, ...
t = 8 fm/c
x [fm]
z [fm]
HEAVY QUARK
GLASMA
E^η
B^η
v1
VORTICITY
Studies on POLARIZATION
dN/dηdpT
link to pA
Δv1 (D0 − D̄0) ⊕ l± from Z0 decay
Z0
l−
l+
e.m. field
B(τ) determination
CME
CVE
[CP violation]
B
σel(T) ELETTRIC CONDUCTIVITY

Back-up Slide

Charm quark vs Bottom quark



Spatial diffusion coefficient of bottom quark



Kinetic theory: $\tau_{th}(b)/\tau_{th}(c) \approx \gamma_c/\ \gamma_b \approx M_b/M_c$

$D_s = \frac{T}{M\gamma} = \frac{T}{M}\tau_{th}$ ideally M independent (M→ ∞)

Results from R_{AA} (p_T) and v_2 (p_T)

In QPM approach → D_s(c) is 30-40% larger than D_s(b)
M→ ∞ limit is not reached for charm

FCC → Bottom fully thermalized

Chiral Magnetic Effect and P &CP violation

Axial current j^5_μ : net handedness flow

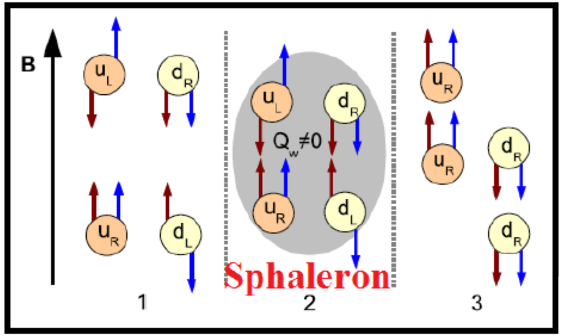
$$\partial^\mu j^5_\mu = 2\sum_f m_f \langle \bar{\psi}_f i\gamma_5 \psi_f \rangle_A - \frac{N_f g^2}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a ,$$

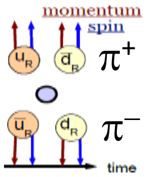
A **sphaleron** drives locally a chiral imbalance $\langle N_L - N_R \rangle \neq 0$ in HotQCD matter

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

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

Momentum
Spin





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

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

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

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

No $\mathcal{C}$-odd but $\mathcal{CP}$-odd

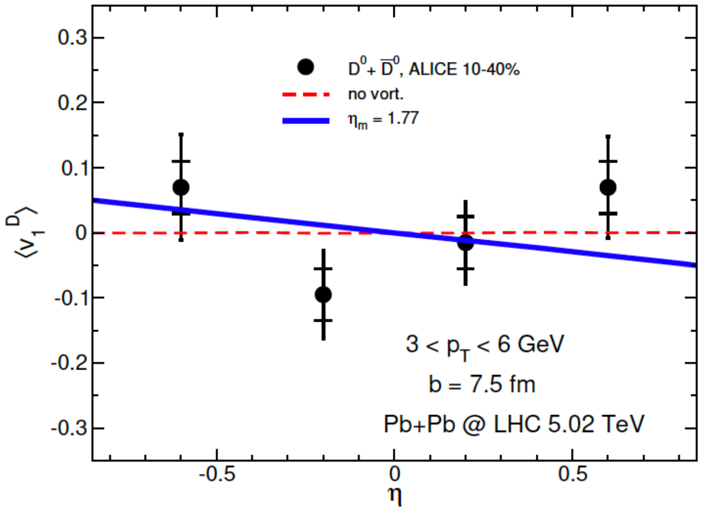
Relaxation time of topological charge $m_q^{-1} \gg \tau_{fireball}$

Expected exp. effect: dipole modulation of azimutal distribution

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

CHE

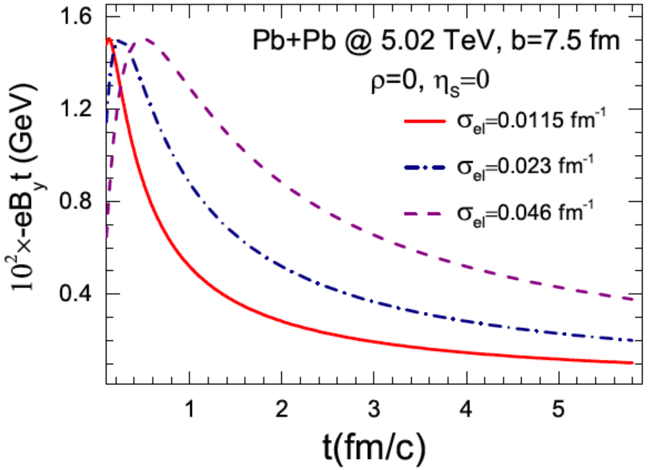
Observed in Dirac semi-metals – Q. Li et al., *Nature Physics* 12 (2016)



0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.5
0
0.5
η
⟨v1D⟩
D0+ D̄0, ALICE 10-40%
no vort.
ηm = 1.77
3 < pT < 6 GeV
b = 7.5 fm
Pb+Pb @ LHC 5.02 TeV

Impact of $\Delta[tB_y(t)]$

Sun Yifeng,Plumari, VG, *arXiv:2104.03742*



$$\frac{d\Delta v_1^c}{dy_z}|_{y_z=0} = -\alpha\frac{\partial \ln f_c}{\partial p_T} + (2\alpha-\beta)\frac{p_T}{m_T^2}$$

- discarding medium interaction
- assuming an elliptic "rigid" bulk
- slow variation of E-B in the transverse plane

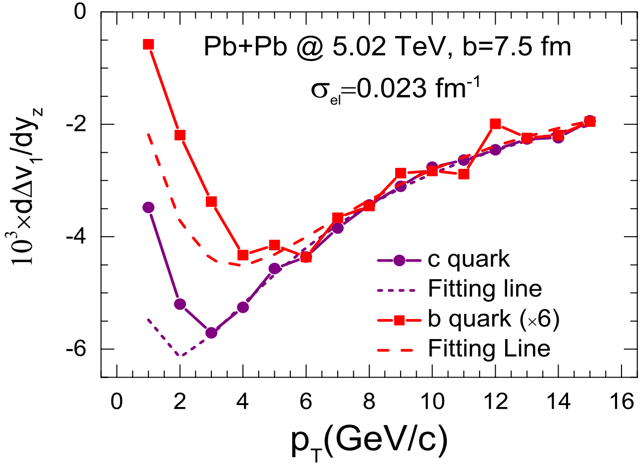
$$\begin{cases} \alpha = |q|K[\tau_1 B_y(\tau_1) - \tau_o B_y(\tau_0)] \\ \beta = |q|K(\lambda - d^2\lambda/dy_z^2)|_{y=0} \\ \lambda(y_z) = \int_{\tau_0}^{\tau_1(p_T)} d\tau\, B_y(\tau, y_z) \end{cases}$$

dominant term

τ_0 formation time

τ_1 escape or freeze-out

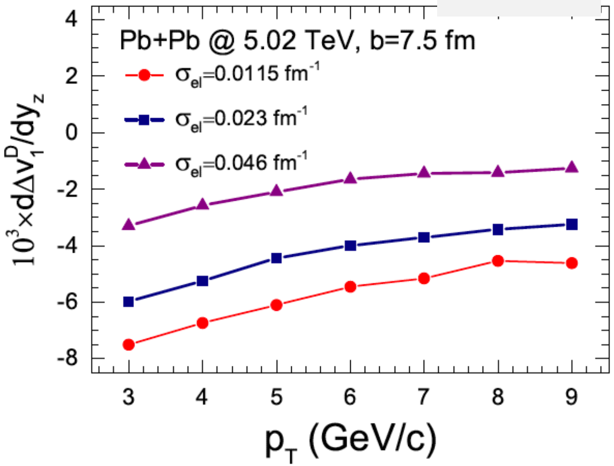
- K depends on space distrib. bulk and charm (also on t_0)
- **α depends on $\Delta[tB_y(t)]$ – implicitly E_x included**
- β smaller unless $\Delta(tBy(t)) \approx 0$



Medium strong interaction negligible at
p_T>3-4 GeV for charm
p_T>6 GeV for bottom

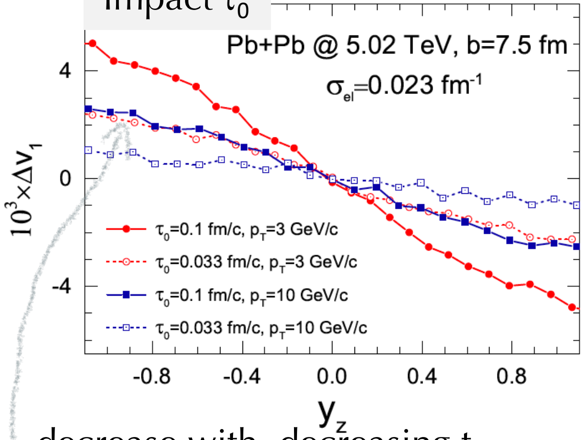
Large σ_{el} longer lifetime
→ smaller Δv1

D meson



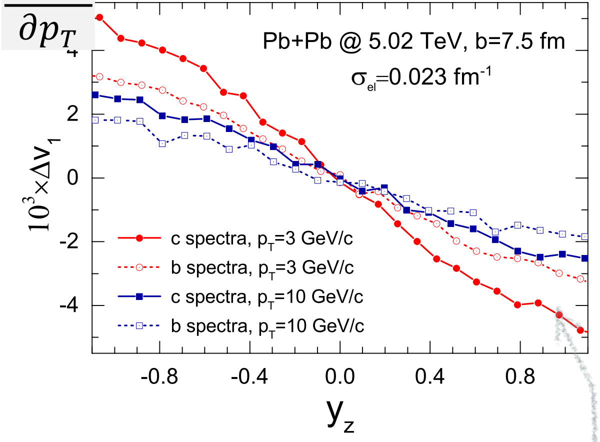
Relevance of particle formation time,mass,spectra

Impact τ_0

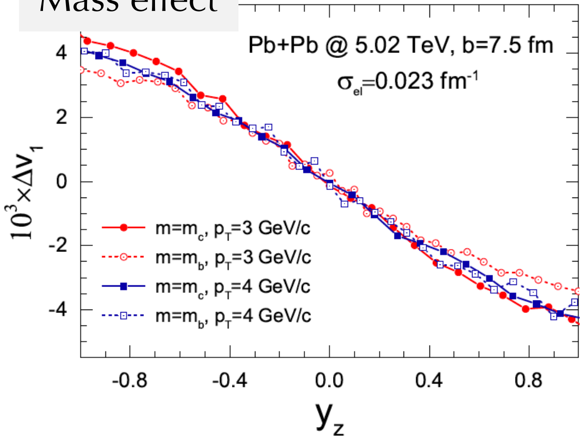


decrease with decreasing t_0

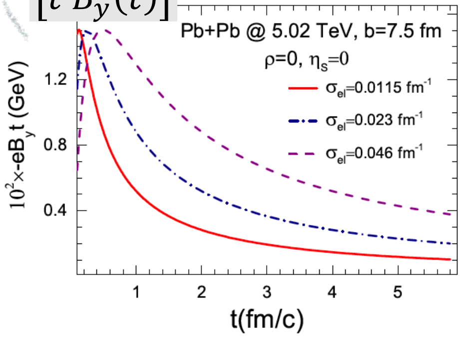
$\frac{\partial \ln f}{\partial p_T}$



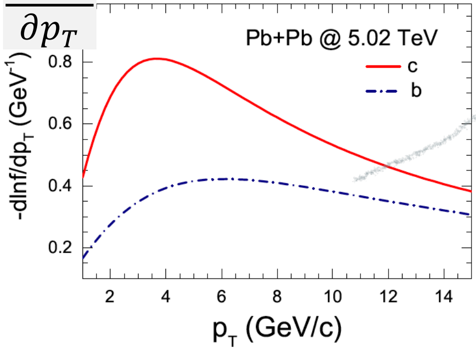
Mass effect



$[t\, B_y(t)]$



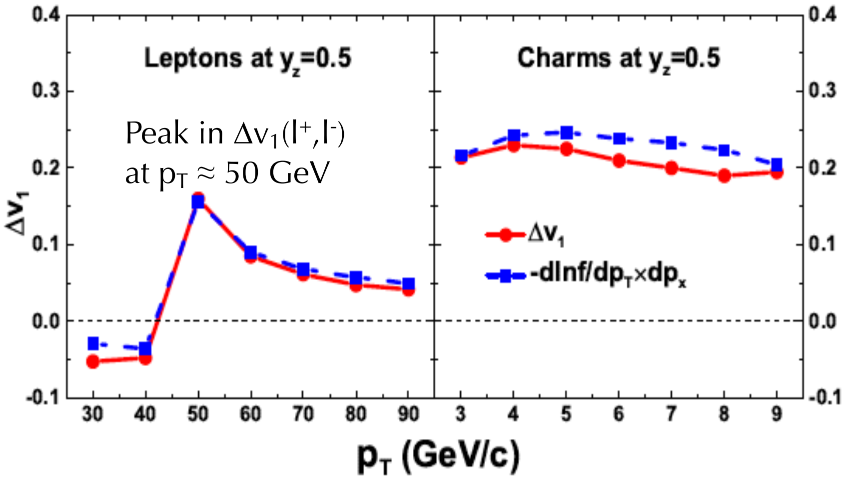
$\frac{\partial \ln f}{\partial p_T}$

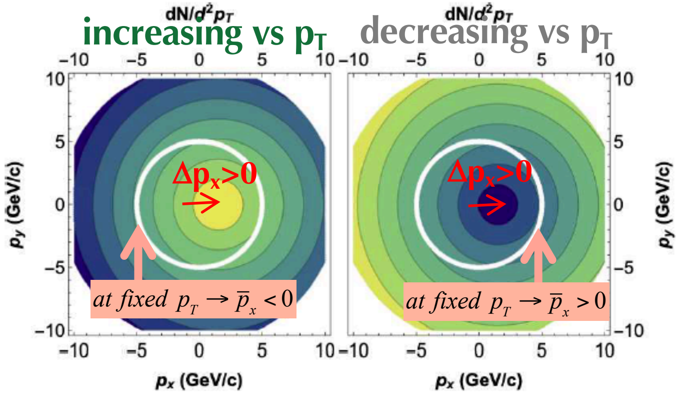


Sun Yifeng,Plumari, VG, *arXiv:2104.03742*

Different t_0 for 2 particle species decorrelate Δv_1 → correlation for D^0 and Z^0

V_1 splitting for leptons from Z^0 decay





Surprises:

*) $\Delta v_1(l^+,l^-) < \Delta v_1(D^0,\underline{D}^0)$

*) even the sign of $\Delta v_1\ (l^+,l^-)$ can be opposite!?

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

Sign change is not due to a sign change of Δp_x that is always positive

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

Never pointed in HIC …a rise and fall p_T spectrum never studied

Improvements…

❖ Several aspects to be investigated more in detail for e.m. field:

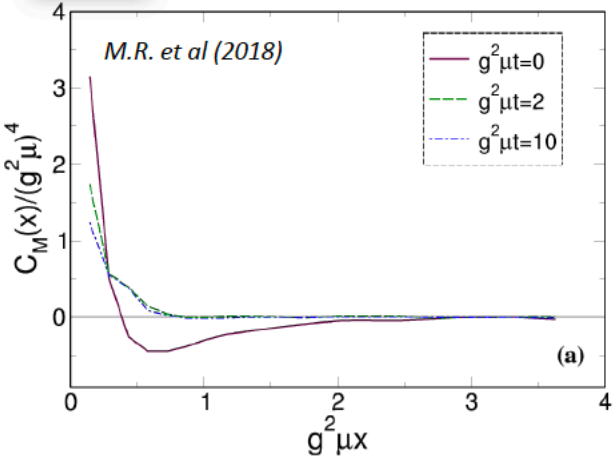
- Better assessment of the magnetic field for t<0.5-1 fm/c: non-eq., $\sigma_{el}(t)$,anomalous…
- Back-reaction to the electromagnetic field of the the fluid, now "rigid charges"
  no rearrengements that can modify the **E-B** balance
- Modification to anisotropic transport coeff. Induced by e.m. field (Hall viscosity,…)
- ….

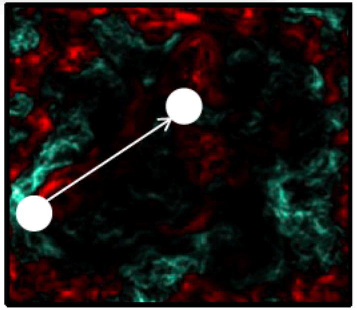
Correlator of color-magnetic field

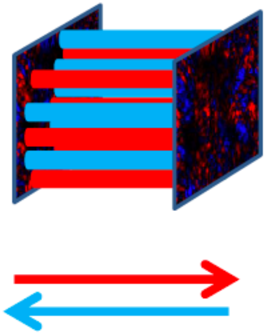
$$\mathcal{G}(x) = \langle \mathrm{Tr}\left[B_z(0) \cdot U_{0\to x} \cdot B_z(x) \cdot U_{x\to 0}\right]\rangle$$

$$U_{0\to x} = e^{ig\int_0^x dx A_x}$$

$$\frac{\mathcal{G}(x)}{(g^2\mu)^4}$$







Fitting form up to $\mathbf{g^2\mu r}\approx 1$:

$$\mathcal{C}(r) \sim \sqrt{\frac{\xi}{r}}e^{-r/\xi}$$

ξ: correlation length

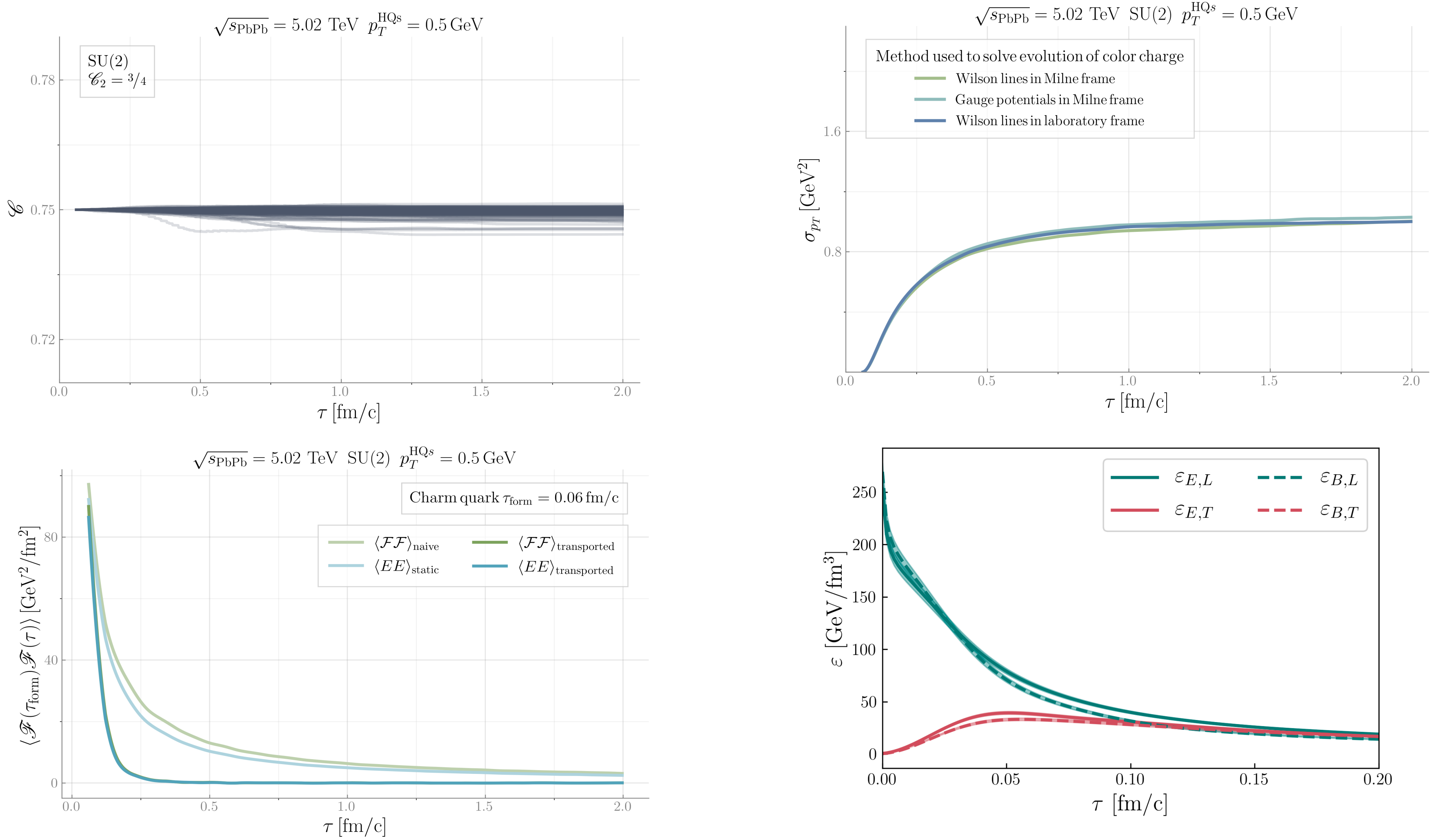
<u>*Initial time*</u>

- Correlation length $\approx 0.3/\mathbf{g^2\mu} \approx 0.06$ fm

  Nucleon size ≈ 1 fm $\gg \xi$: *domains on sub-nuclear scale*

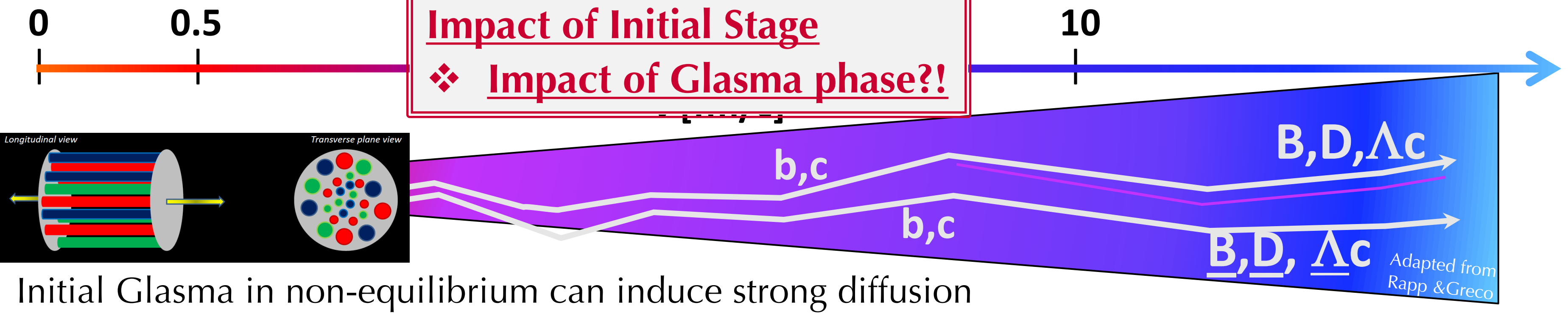
- Anti-correlation on length scale $\approx 1/\mathbf{g^2\mu}$ on the transverse plane

  Antiferromagnetic-like ordering on length scale $\approx 1/\mathbf{g^2\mu}$



$\sqrt{s_{\rm PbPb}} = 5.02$ TeV $p_T^{\rm HQs} = 0.5$ GeV
SU(2)
$\mathscr{C}_2 = 3/4$
$\mathscr{C}$
0.78
0.75
0.72
0.0
0.5
1.0
1.5
2.0
τ [fm/c]
$\sqrt{s_{\rm PbPb}} = 5.02$ TeV SU(2) $p_T^{\rm HQs} = 0.5$ GeV
Method used to solve evolution of color charge
Wilson lines in Milne frame
Gauge potentials in Milne frame
Wilson lines in laboratory frame
σ_{p_T} [GeV^2]
1.6
0.8
0.0
0.5
1.0
1.5
2.0
τ [fm/c]
$\sqrt{s_{\rm PbPb}} = 5.02$ TeV SU(2) $p_T^{\rm HQs} = 0.5$ GeV
Charm quark $\tau_{\rm form} = 0.06$ fm/c
$\langle \mathcal{F}\mathcal{F} \rangle_{\rm naive}$
$\langle \mathcal{F}\mathcal{F} \rangle_{\rm transported}$
$\langle EE \rangle_{\rm static}$
$\langle EE \rangle_{\rm transported}$
$\langle \mathscr{F}(\tau_{\rm form})\mathscr{F}(\tau) \rangle$ [GeV^2/fm^2]
80
40
0
0.0
0.5
1.0
1.5
2.0
τ [fm/c]
$\varepsilon_{E,L}$
$\varepsilon_{B,L}$
$\varepsilon_{E,T}$
$\varepsilon_{B,T}$
ε [GeV/fm^3]
250
200
150
100
50
0
0.00
0.05
0.10
0.15
0.20
τ [fm/c]

Studying the HF in uRHIC



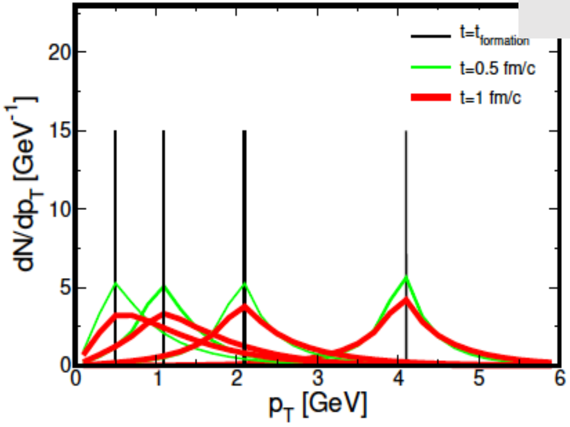
Impact of Initial Stage

❖ **Impact of Glasma phase?!**

Initial Glasma in non-equilibrium can induce strong diffusion

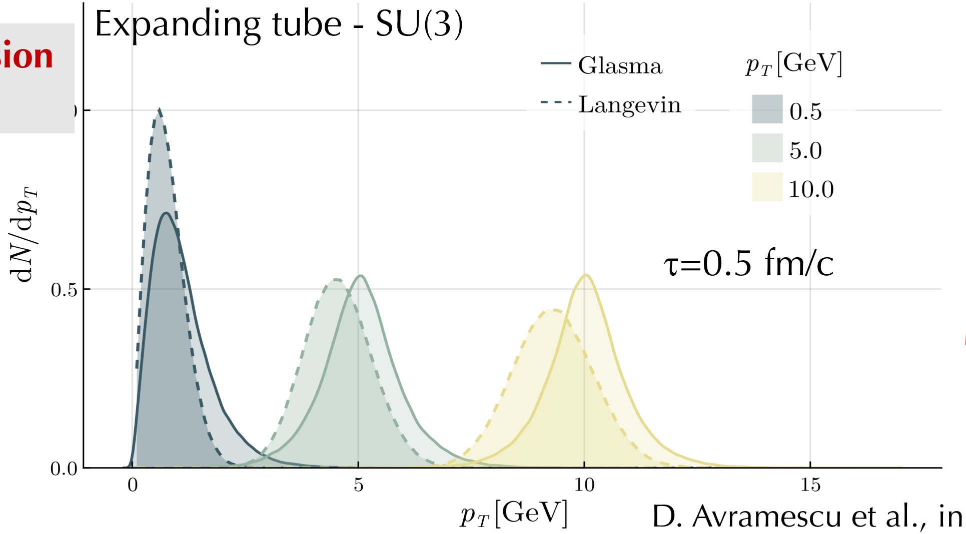
- M.Ruggieri and S.K. Das, PRD98 (2018)

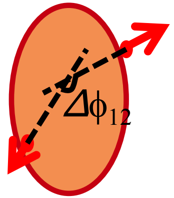
Static box- SU(2)



Strong diffusion
No drag

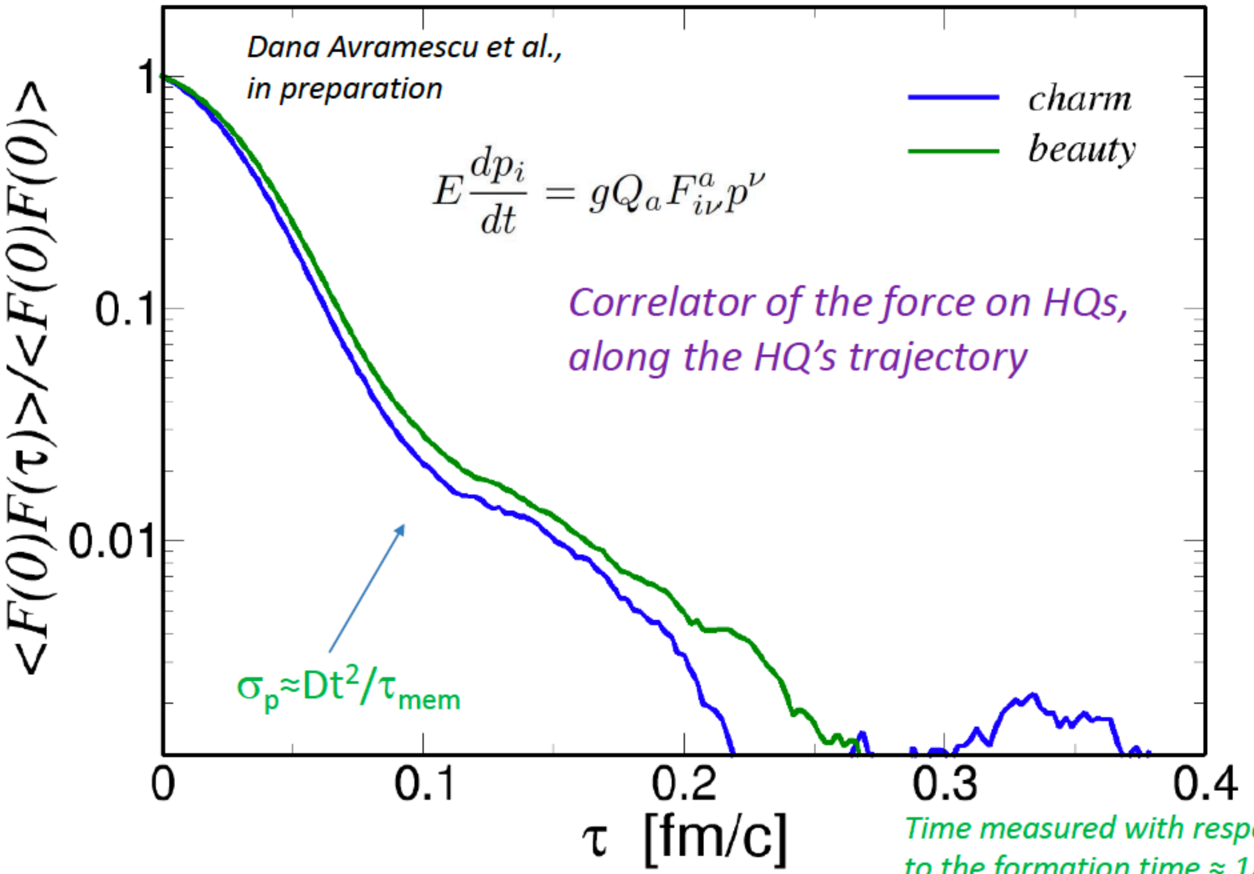
Expanding tube - SU(3)





D. Avramescu et al., in preparation

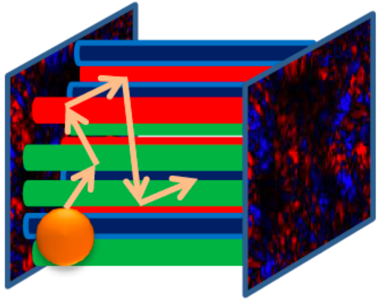
Memory for the HQs diffusion in EvGlasma



Time measured with respect to the formation time ≈ 1/2m

Comparison Glasma vs Langevin in early stage – SU(3)

Charm in the Glasma and Langevin starting at t_{form}=0.08 fm/c
Same underlying bulk energy density (central PbPb@5.02ATeV)
LV: Drag & Diffusion tuned to R_{AA}

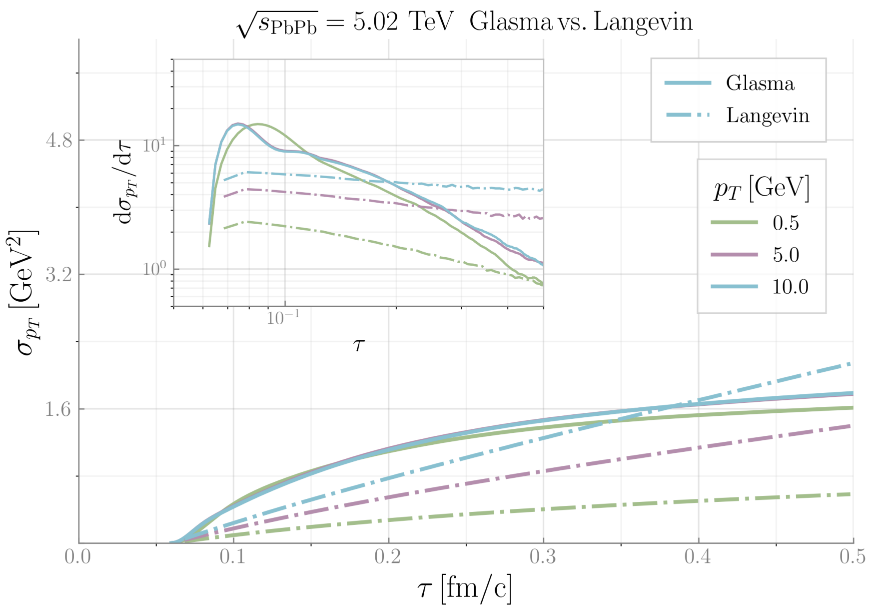


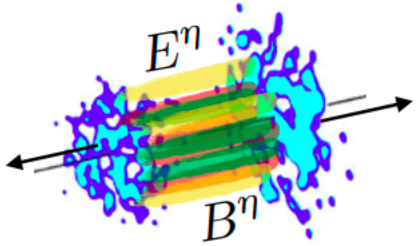
Memory effect

- *Early time: $\sigma_p \approx Dt^2/\tau_{mem}$*
- *Later time time: $\sigma_p \approx 2Dt$*

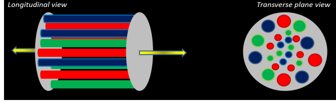
Like LV

Evolution of variance of the distribution





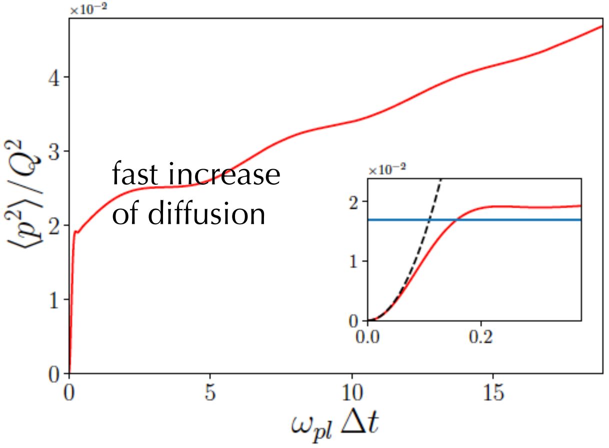
Fast early diffusion ($M \rightarrow \infty$)



K. Boguslavski, A. Kurkela, T. Lappi and J. Peuron, JHEP09 (2020) 077 in SU(3) for $M \rightarrow \infty$

Not really a glasma, but an oveoccupied isotropic Gluon plasma: transverse components at t_0

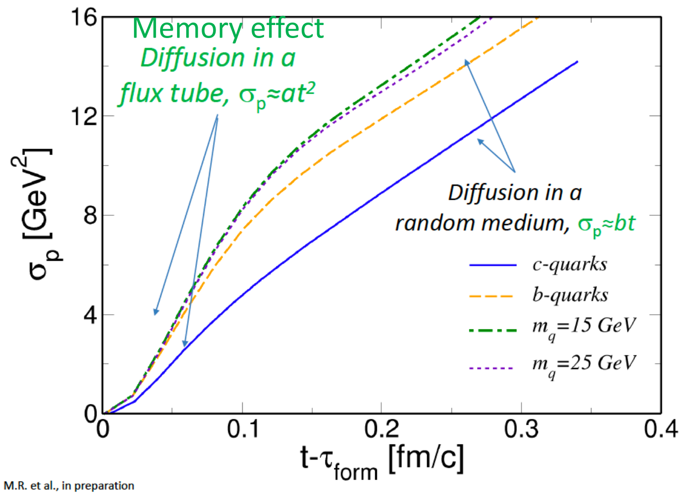
Assuming $M \rightarrow \infty$
Static Box



Correlator method

$$\langle \dot{p}_i(t)\dot{p}_i(t')\rangle = \frac{g^2}{2N_c}\langle E_i^a(t)E_i^a(t')\rangle$$

Mass dependence in our approach

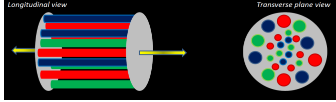


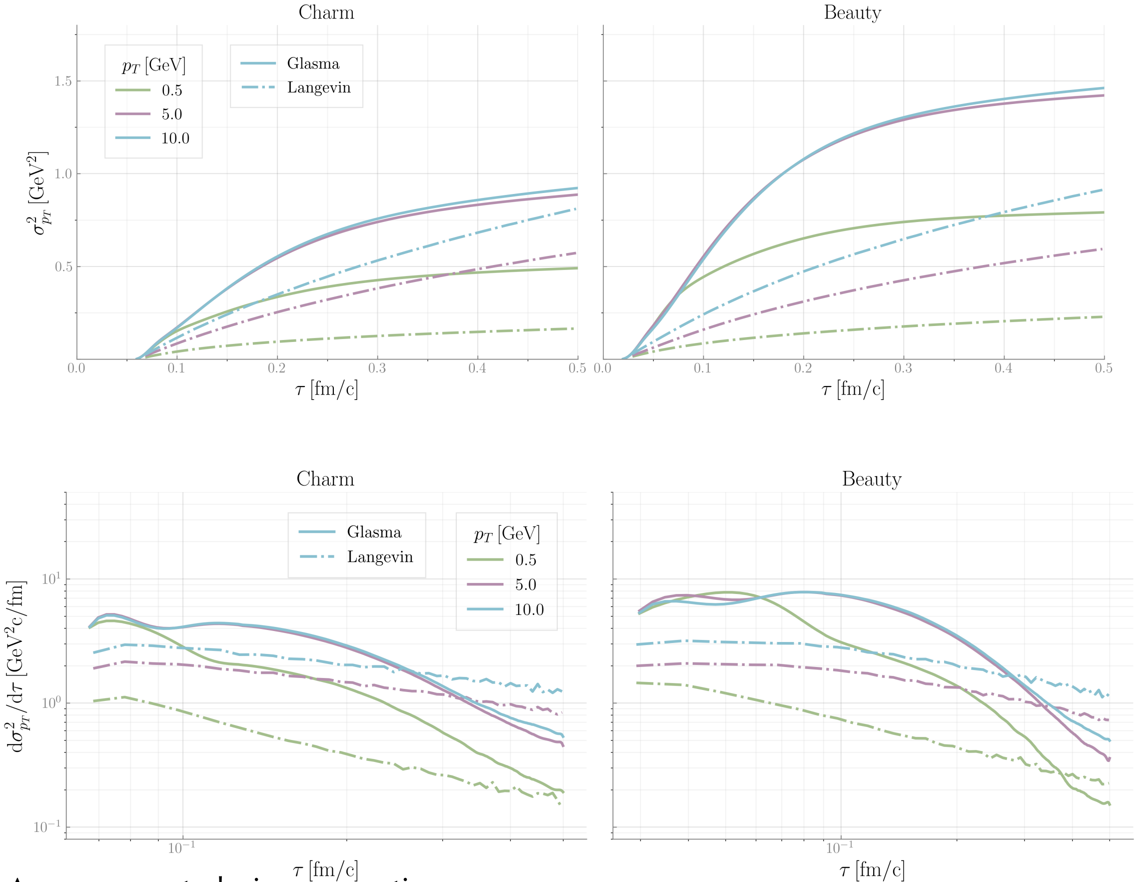
- *Early time: $\sigma_p \approx Dt^2/\tau_{mem}$*
- *Later time time: $\sigma_p \approx 2Dt$*

M. Ruggieri et al., arXiv:21**

M.R. et al., in preparation

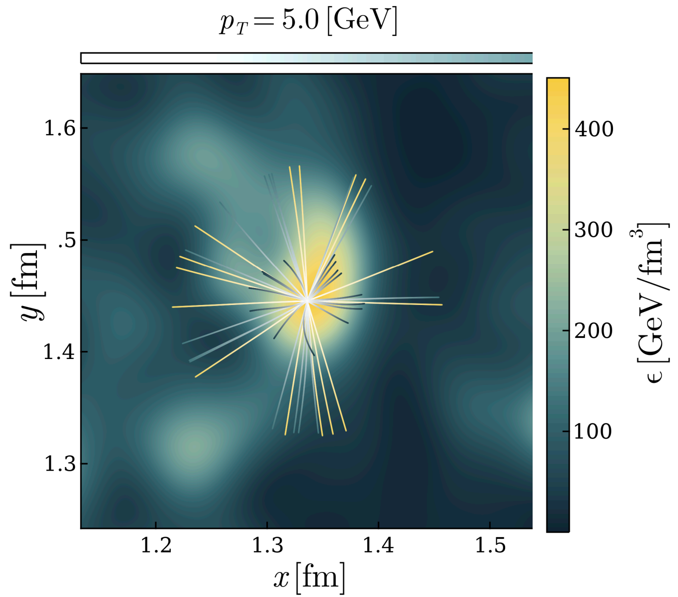
Mass effect: Charm vs Bottom in Glasma and LV





D. Avramescu et al., in preparation

Large mass -> motion
stays more in the correlated tube



However bottom as a flat p_T distribution so folding by it. The effective difference may be even smaller than for charm

Naive discretization

Proceed with caution

- Non-Abelian gauge transformations:

$$A_\mu(x) \mapsto \mathsf{U}(x)A_\mu(x)\mathsf{U}^\dagger(x) + \frac{1}{ig}\mathsf{U}(x)\partial_\mu\mathsf{U}^\dagger(x)$$

- Discretizing the gauge field on a lattice will break gauge invariance.

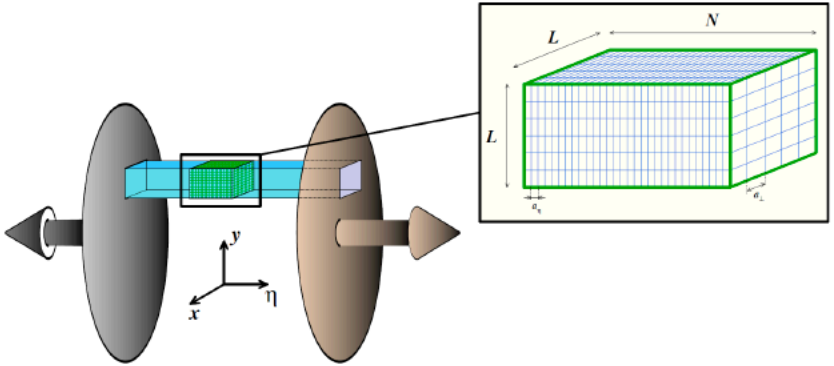


Figure from F. Gelis - Color Glass Condensate and Glasma [1211.3327]

CPIC adapted to Glasma

Evolution of color charge

- When the **nearest grid point** on the lattice changes, color rotate the charge with the appropriate Wilson lines.
- Glasma in temporal gauge $A_\tau = 0$ with boost-invariance

$$\mathcal{U}(\tau,\tau_0) = \mathscr{P}\exp\left\{-\mathrm{i}g\int_{x_T(\tau_0)}^{x_T(\tau)}\mathrm{d}x'^i A_i\left(x'_T(\tau)\right) - \mathrm{i}g\underbrace{\int_{\eta(\tau_0)}^{\eta(\tau)}\mathrm{d}\eta'}_{\eta(\tau)-\eta(\tau_0)}\underbrace{A_\eta\left(x_T(\tau)\right)}_{\mathrm{indep}(\eta')}\right\}.$$

- Numerically approximate as $\mathcal{U}(\tau_i,\tau_f)\approx\mathcal{U}(\tau_i,\tau_{i+1})\mathcal{U}(\tau_{i+1},\tau_{i+2})\ldots\mathcal{U}(\tau_{f-1},\tau_f)$

CPIC adapted to Glasma

Evolution of color charge

- Numerically $\left[\int \mathrm{d}x^i A_i, \delta\eta_n A_\eta\right] \simeq 0$ thus a Wilson line in a single simulation step is

$$\mathcal{U}(\tau_{n-1},\tau_n) \simeq \underbrace{\exp\left\{ig \int_{\boldsymbol{x}_{n-1}}^{\boldsymbol{x}_n} \mathrm{d}x'^i A_i\left(\boldsymbol{x}'_n\right)\right\}}_{U_{\boldsymbol{x}_{n-1},\hat{i}}(\tau_n)} \times \underbrace{\exp\left\{ig\delta\eta_n A_\eta(\boldsymbol{x}_n)\right\}}_{\equiv U_{\boldsymbol{x}_n,\hat{\eta}}(\tau_n)}$$

where $U_{\boldsymbol{x}_n,\hat{i}}$ is a transverse gauge link along direction $\hat{i}$ and $U_{\boldsymbol{x}_n,\hat{\eta}}$ an artificially constructed Wilson line along the $\hat{\eta}$ direction.