Probing Electromagnetic Field with Heavy Quarks and Leptons from Z^0 decay

Yifeng Sun - University of Catania/INFN-LNS

Istituto Nazionale di Fisica Nucleare

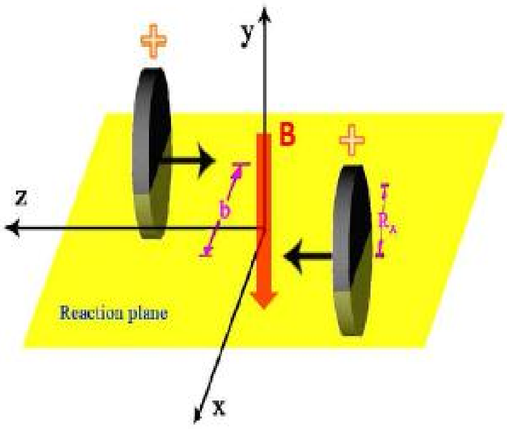
Collaborators:

S. Plumari, L. Oliva, V. Greco

Outline

- Impact of e.m. fields in uRHICs
- Probing e.m. fields with v_1 splitting of heavy quarks
- Probing e.m. fields with v_1 splitting of leptons from Z^0 decay
- What we can learn from the measurements of v_1 splitting?

Impact of e.m. fields in uRHICs



Strong B field induces:

- Chiral magnetic effect (CME)
  - P & CP violation of QCD

  D.E. Kharzeev et al., NPA 803 (2008), 227-253
  K. Fukushima et al., PRD 78 (2008), 074003

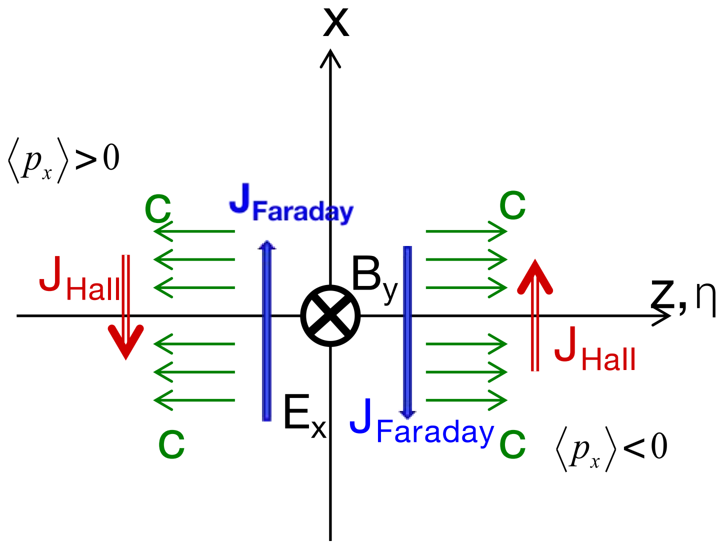
- Chiral magnetic wave (CMW)
  - Gapless collective exciation in QGP

  D.E. Kharzeev et al., PRD 83 (2011), 085007
  Y. Burnier et al., PRL 107 (2011), 052303

- Hyperon spin polarization splitting
  - Most vortical fluid

  STAR, Nature 548 (2017), 62-65

Probing e.m. fields with v_1 splitting of heavy quarks



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

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

$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$ — Faraday (decaying B) — Hall

- Delicate balance between E and B fields
  - E wins -> negative slope of v_1 vs y_z
  - B wins -> positive slope of v_1 vs y_z

- HQs best probe for v_1 induced by e.m. fields:
  - $t_{form} \approx 0.08$ fm/c when B_y is ≈ its maximum
  - $\tau_{th}(c) \approx \tau_{QGP} >> \tau_{e.m}$ (keep more memory effects)

U. Gursoy et al., PRC 89 (2014), 054905
S.K. Das et al., PLB 768 (2017), 260-264

E.M. fields with constant conductivity

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

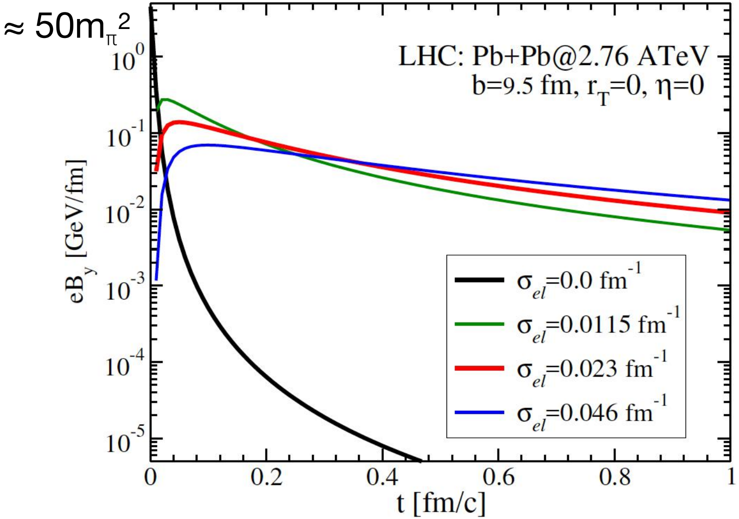
Analytic solution of the above Maxwell equations assuming constant conductivity

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

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

ρ is the transverse charge density of spectors

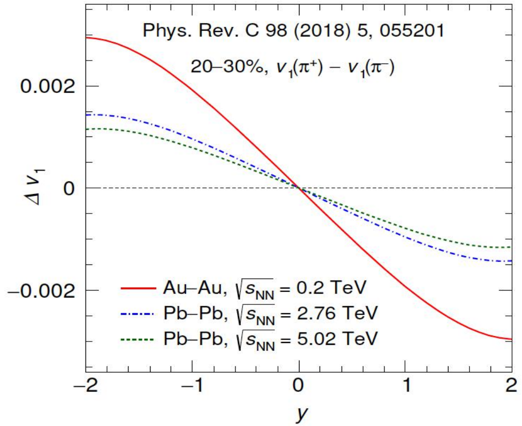
U. Gursoy et al., PRC 89 (2014), 054905
H. Li et al., PRC 94 (2016), 044903



Assumptions:

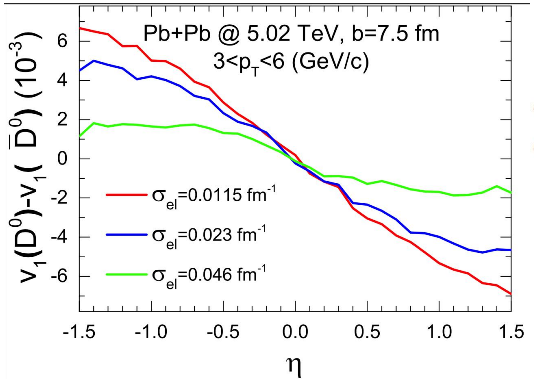
- Medium at t<0
- Electric Conductivity constant
- No back reactions in the bulk due to Lorentz force
- No e-b-e fluctuations

Tensions between exper. and theo. results (5TeV PbPb)



U. Gursoy et al., PRC 98 (2018), 055201

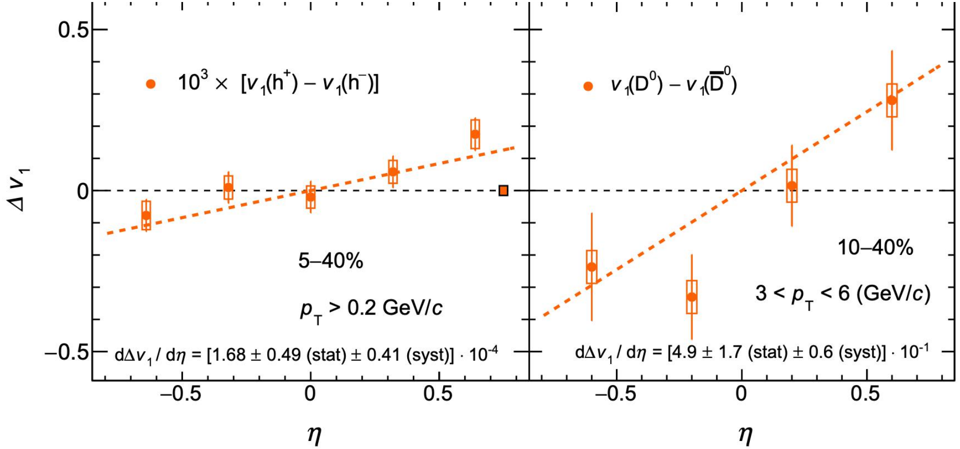
Negative slope -1*10^{-3}:
E wins (Faraday effect)
- conductivity 0.023 fm^{-1}



Our study of D mesons

$$dx_i = \frac{p_i}{E}dt,$$
$$dp_i = -\Gamma p_i dt + \rho_i\sqrt{2Ddt} + q(E_i + \epsilon_{ijk}v_jB_k)dt,$$

Negative slope -4*10^{-3}:
E wins (Faraday effect)
- conductivity 0.0115, 0.023, 0.046 fm^{-1}



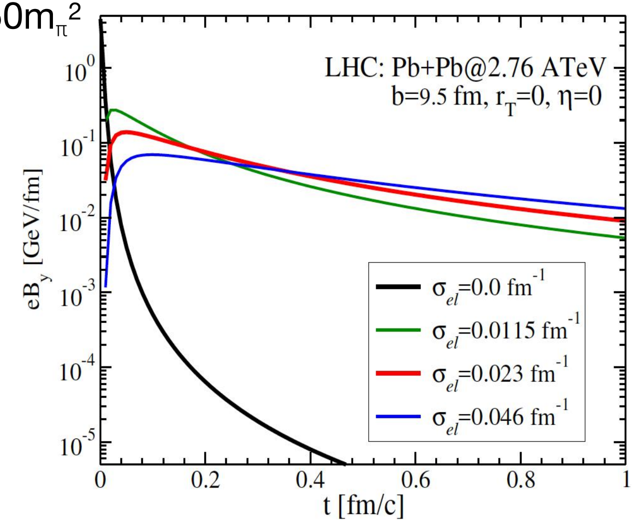
ALICE, PRL 125 (2020), 022301

Positive slope : B wins (Hall effect)

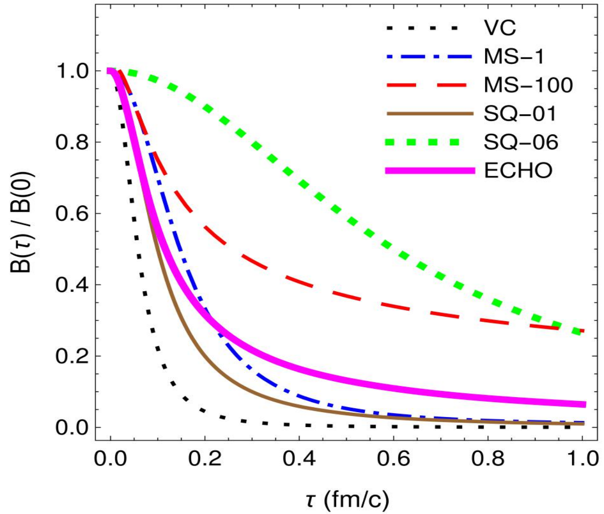
- Strong tensions between experiments and numerical calculations
- Magnitude of slope is large 4.9*10^{-1} D mesons

E.M. field is not really under control

$\approx 50 m_\pi^2$



CME studies

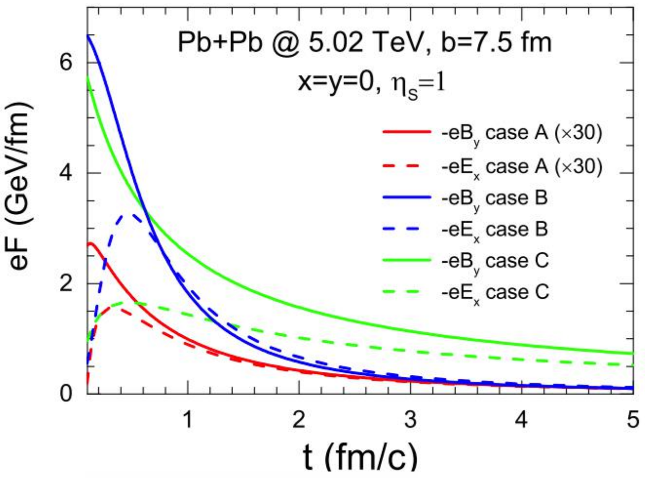


S. Shi et al., AP 394 (2018), 50-72
L. Mclerran et al., NPA 929 (2014) 184
G. Inghirami et al., EPJC 76 (2016), 659

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} even before t=0 (need more realistic simulations)
- lQCD ?
- Early time what is σ_{el} in the Glasma + more exotics: Chiral topological charge [arXiv:2002.05047,Tuchin] etc..

E.M. field varaiation



Case A

E-B fields like U. Gursoy et al., PRC 89 (2014), 054905

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

Case B and C like the CME Y. Sun et al., PLB 816 (2021), 136271

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

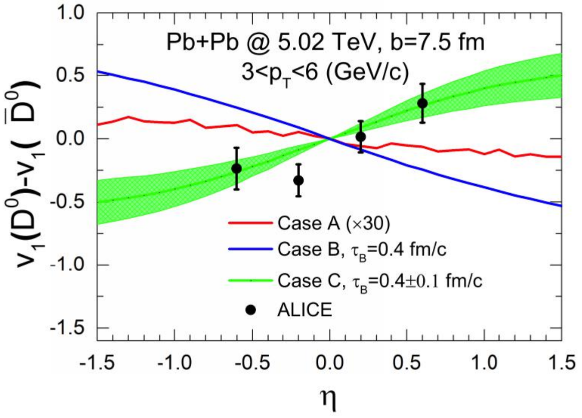
$$\boxed{B(\tau) = eB_0/(1+\tau^2/\tau_B^2)}$$

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

E_x is evaluated by the Faraday's Law

$$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t:$$

eB_0 the value t=0 in vaccum



Y. Sun et al., PLB 816 (2021), 136271

Case C can reproduce experimental data:

- Case A slope: -4*10^{-3}, Case B slope: -0.42, Case C slope: 0.44
- Case B and C has same eB_0 and τ_B, and they are similar at t<1 fm/c: The difference comes from the later time evolution of B
- Time derivative of B_y(t) even more relevant than absolute values: A slowly decay B leads to a relative smaller E, and B (Hall effect) wins over E

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

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

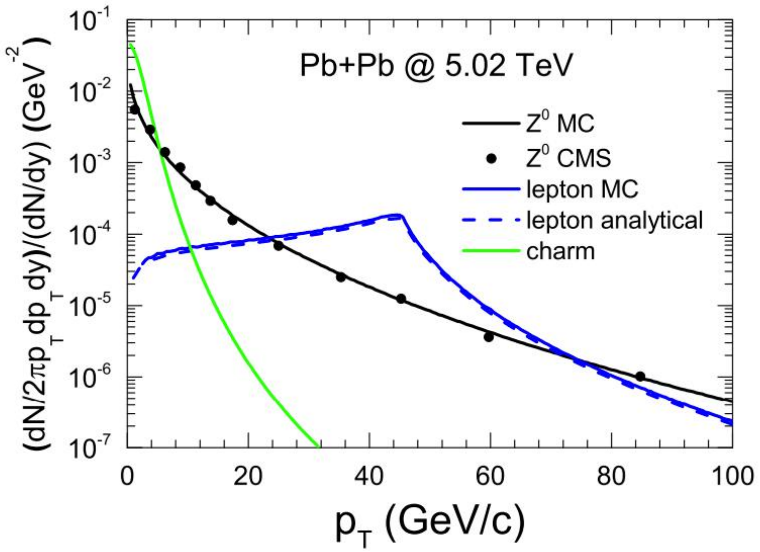
Is there some complementary way of proving it?

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

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

→ Probing the electromagnetic fields in ultra-relativistic collisions with leptons from Z^0 decay

Why leptons from Z^0 decay



Y. Sun et al., PLB 816 (2021), 136271

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

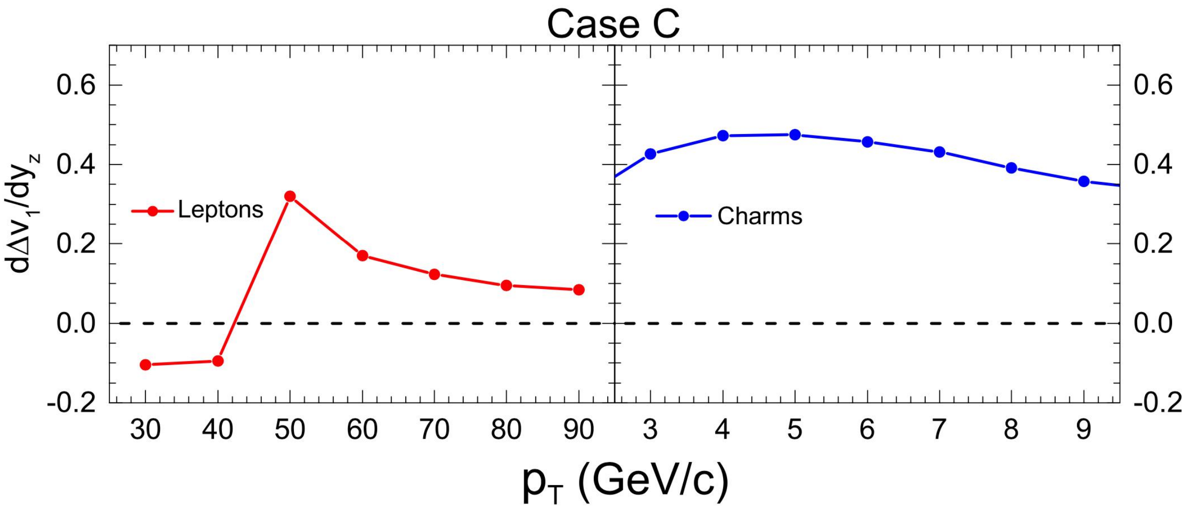
- Clearer observables
- Leptons from Z^0 decay are separable by other sources
- $\tau_{decay}(Z^0)= \tau_{form}(\mathrm{charm})=0.08$ fm/c: they go through the e.m. fields at the same time → meanfigul look at the correlation $\Delta v_1(D^0,\overline{D}^0)$ and $\Delta v_1(l^+,l^-)$

<u>What one expects?</u>

- No damping from medium interaction
- Massless more easily to drag by e.m. fields
- Charge 1.5 times larger

<u>One expects same sign and $\Delta v_1(l^+,l^-) > \Delta v_1(D^0,D^0)$?!</u>

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



Y. Sun et al., PLB 816 (2021), 136271

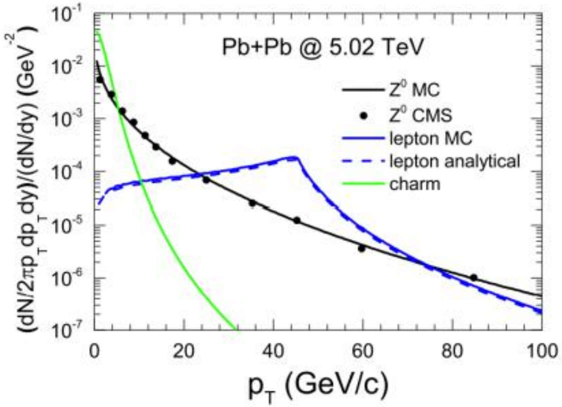
Surprises:

- $d\Delta v_1/dy(l^+,l^-) < d\Delta v_1/dy(D^0,\bar{D}^0)$ even if $\Delta p_X(l) \approx 2^* \Delta p_X(c)$ due to Lorentz force

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

- even the sign of $\Delta v_1\ (l^+,l^-)$ can be opposite!? not because E wins

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



Slope of letpons from Z^0 decay peaks p_T=at 50 GeV, and increase first and then decrease

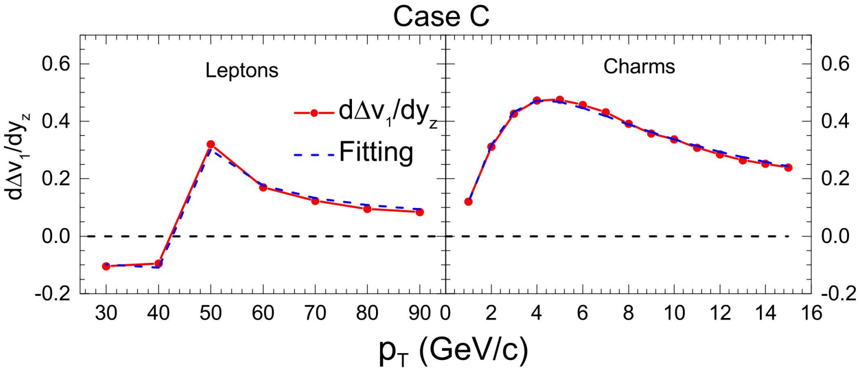
$\boxed{\text{Peak in } \Delta v_1(l^+,l^-) \text{ at } p_T \approx 50 \text{ GeV consistent with the large } \Delta v_1(D^0)\ ?}$

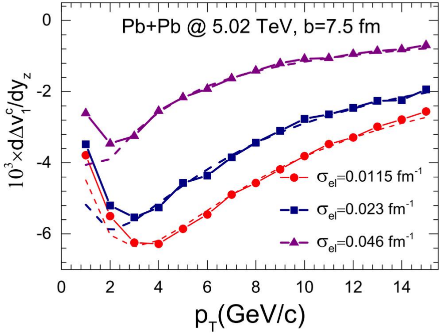
General conclusion for v_1 splitting induced by e.m. field: 1

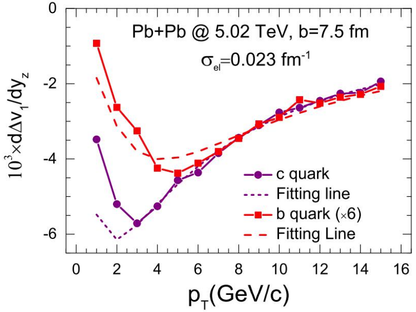
Y. Sun et al., EPJP 136 (2021), 726

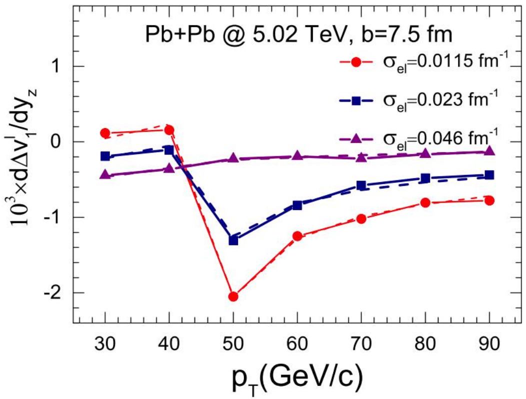
$$\boxed{\frac{d\Delta v_1^c}{dy_z}\Big|_{y_z=0} = -\alpha\frac{\partial \ln f_c}{\partial p_T} + (2\alpha-\beta)\frac{p_T}{m_T^2}}$$

f is spectra of charged particles, α and β are p_T independent relating to e.m. fields directly









- p_T dependence of ***d***$\Delta v_1/dy$ applies to charm and bottom quarks and leptons from Z^0 decay, and with different configurations of e.m. fields (Case C and Case A with σ_{el}=0.0115, 0.023, 0.046 fm^{-1})
- Low p_T derivation for charm and bottom due to QGP interaction

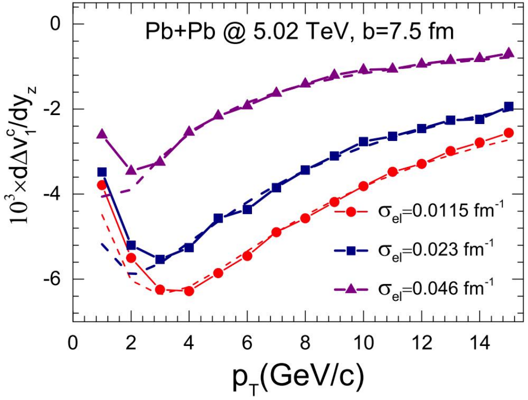
General conclusion for v_1 splitting induced by e.m. field: 2

Y. Sun et al., EPJP 136 (2021), 726

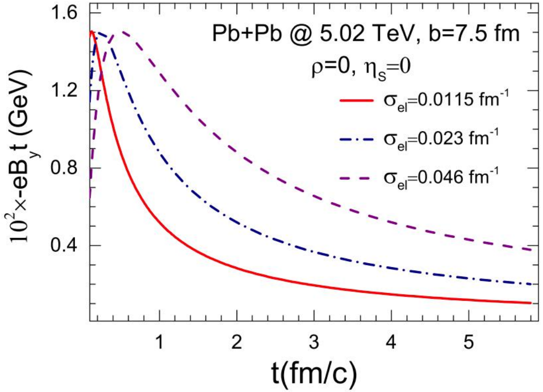
$$\alpha = |q|K[\tau_1 B_y(\tau_1) - \tau_o B_y(\tau_0)]$$

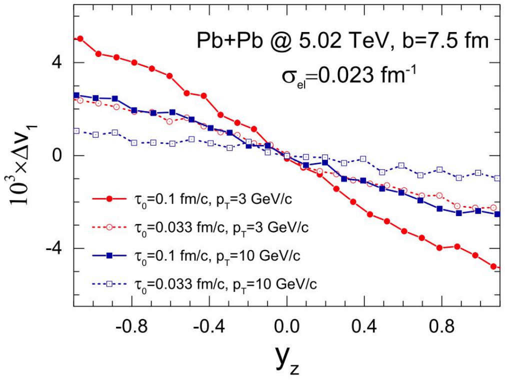
$$\frac{d\Delta v_1^c}{dy_z}|_{y_z=0} = -\alpha \frac{\partial \ln f_c}{\partial p_T} + (2\alpha - \beta)\frac{p_T}{m_T^2}$$

- K is a constant less than 1; t_0 is the formation time; t_1 is the time get rid of e.m. fields~ fm/c



- **α**=6.3, 3.6, 0 MeV with σ_{el}=0.0115, 0.023, 0.046 fm^{-1}, proportional to tB_y variation

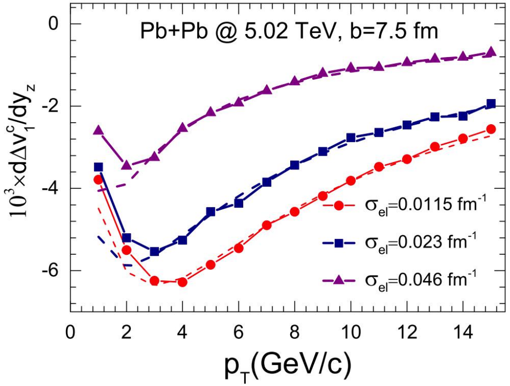


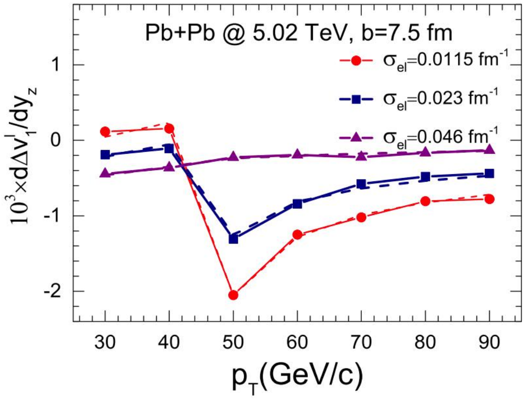


- **α** is smaller when t_0 changes from 0.1 to 0.033 fm/c, due to smaller variation of tB_y

Correlation between v_1 splitting of D^0-$\bar{D}^0$ and l^+-l^- from Z^0 decay

Y. Sun et al., EPJP 136 (2021), 726





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

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

- Extracted from the p_T dependence of $d\Delta v_1/dy$ of **leptons and charm quarks**, **α ratio for Case A with** σ_{el}=0.0115, 0.023 fm^{-1} **are 8.7 MeV/6.3 MeV=1.4 and 4.7 MeV/3.6 MeV=1.3, for Case C is 1.5 GeV/0.75 GeV=2, close to their charge ratio 1.5 for very different e.m. fields: order of 3**
- This correlation applies to all kinds of e.m. fields due to charm and these leptons experiencing same e.m. fields and being produced at similar formation time 0.08 fm/c
- The measurements of this correlation indicates e.m. fields origin

Summary & Outlook

- One can probe e.m. fields from v_1 splitting of charmed mesons and leptons from Z^0 decay
- v_1 splitting induced by e.m. fields has an unverisal form and tells tBy variation
- The correlation between v_1 splitting of charmed mesons and leptons from Z^0 decay applies to all e.m. fields; strong indication of e.m. field origin.
- Need better simulation of magnetohydrodynamics to get e.m. fields spaital and time evolution

There are more things to do and to learn than expected!