SQM 2022
The 20th International Conference on Strangeness in Quark Matter
13–17 June 2022 Busan, Republic of Korea

Probing electromagnetic fields with heavy quarks and Z^0 decaying leptons and Z^0 leptonic invariant mass in uRHICs

Yifeng Sun
sunyfphy@sjtu.edu.cn
Shanghai Jiao Tong University

Collaborators:
S. Plumari, V. Greco and X.N. Wang

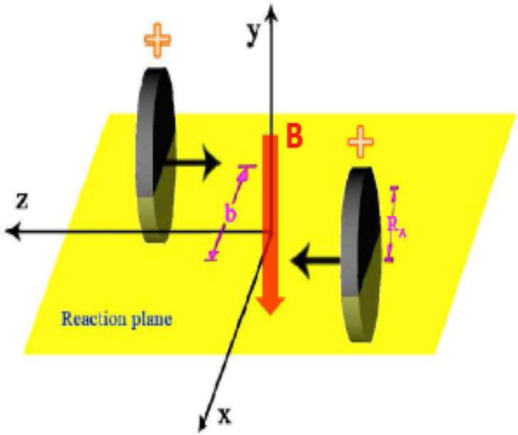
Refs：PLB 816, 136271 (2021); EPJP 136, 726 (2021); PLB 827, 136962 (2022)

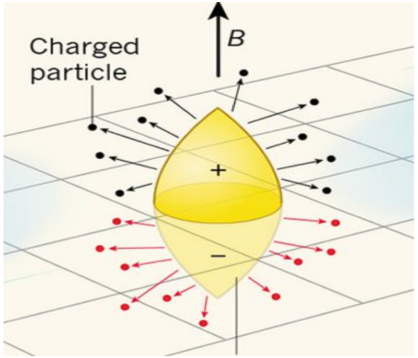
Outline

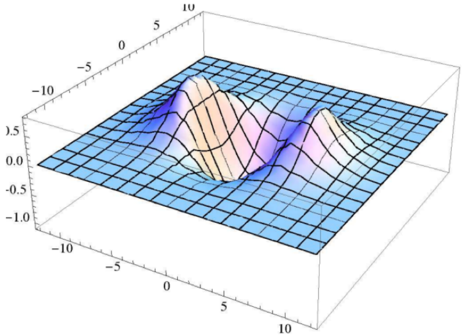
- **Impact of e.m. fields in uRHICs**
- **Probing e.m. fields with v_1 splitting of heavy quarks and leptons from Z^0 decay**
- **The general behavior of charge dependent flows induced by e.m. fields**
- **Modification of Z^0 leptonic invariant mass by e.m. fields**

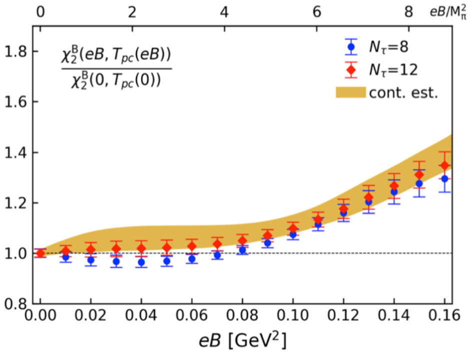
Impact of electromagnetic (e.m.) fields in uRHICs

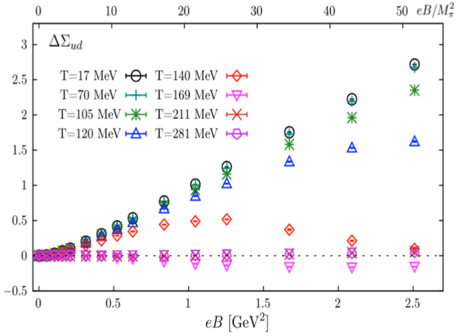
- **Many Impacts: Chiral magnetic effect (CME), Chiral magnetic wave (CMW), Hyperons polarization splitting, Chiral condensate, Fluctuation of conserved charge and so on**







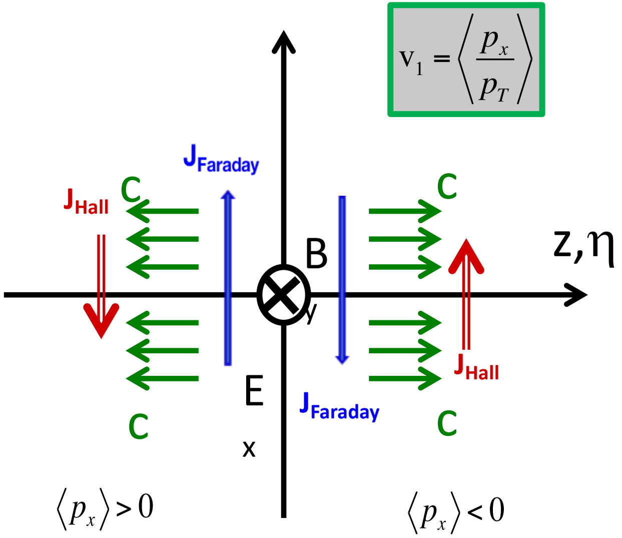




D.E. Kharzeev et al., NPA 803 (2008)
Y. Burnier et al., PRL 107 (2011), 052303
STAR, Nature 548 (2017), 62-65
H.T. Ding et al., PRD 105 (2022), 034514
J.H. Liu, QM 2022

Probing e.m. fields with v_1 splitting of heavy quarks and leptons from Z^0 decay

Probing e.m. fields with v_1 splitting of charged particles



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

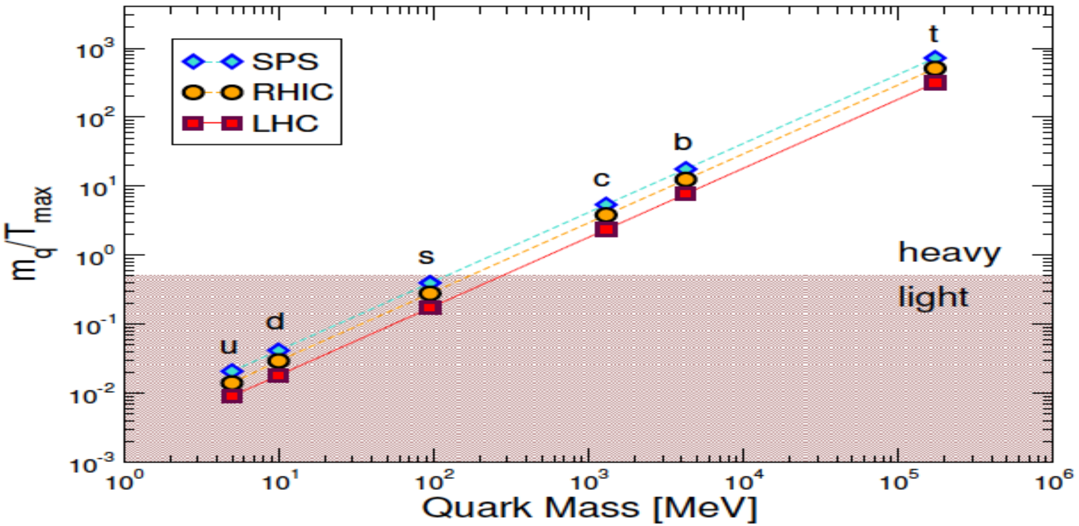
$$\boldsymbol{F}_{ext} = q\mathbf{E} + \frac{q}{E_p}(\boldsymbol{p}\times\boldsymbol{B})$$

Faraday (decaying B) — Hall

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

❖ **Delicate balance between E and B**
- ✓ E wins -> negative slope Δv_1 vs y_z between positively and negatively charged particles
- ✓ B wins -> positive slope Δv_1 vs y_z

Why heavy Quarks (HQs)?



- **HQs best probe for v_1 induced by e.m. fields:**
    1. pQCD hard processes
    2. negligible thermal production
    3. $t_{form} \approx 0.08$ fm/c when B_y is ≈ its maximum and witness of all the QGP evolution
    4. $\tau_{th}(c) \approx \tau_{QGP} >> \tau_{e.m}$ (keep more memory effects)

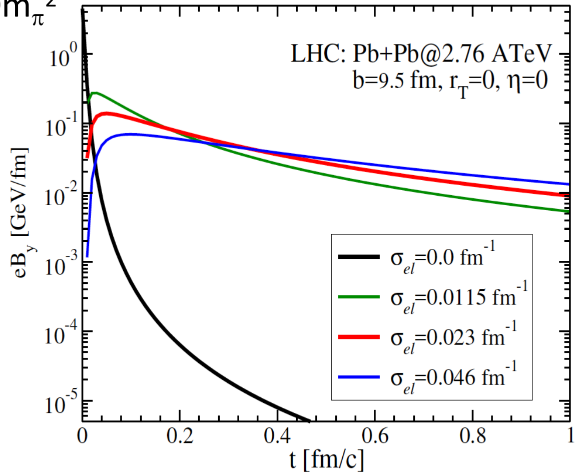
E.M. fields

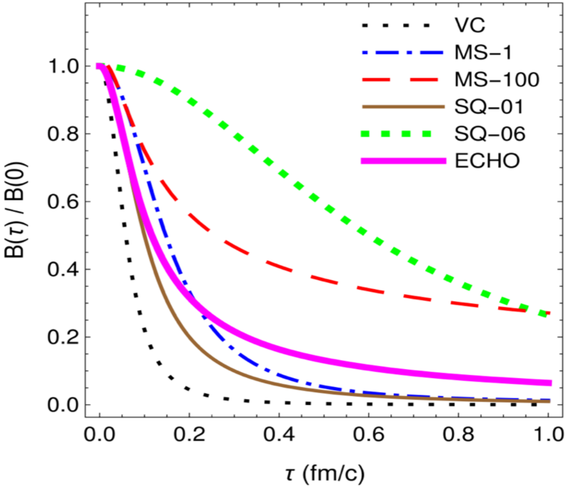
$$\left(\nabla^2 - \partial_t^2 - \sigma_{el}\,\partial_t\right)\boldsymbol{B} = -\nabla\times\boldsymbol{J}_{ext},$$
$$\left(\nabla^2 - \partial_t^2 - \sigma_{el}\,\partial_t\right)\boldsymbol{E} = -\nabla\rho_{ext} + \partial_t\boldsymbol{J}_{ext},$$

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

❖ **Assuming constant conductivity gives an analytical and simple solution of the Maxwell equations**

$\approx 50 m_\pi^2$

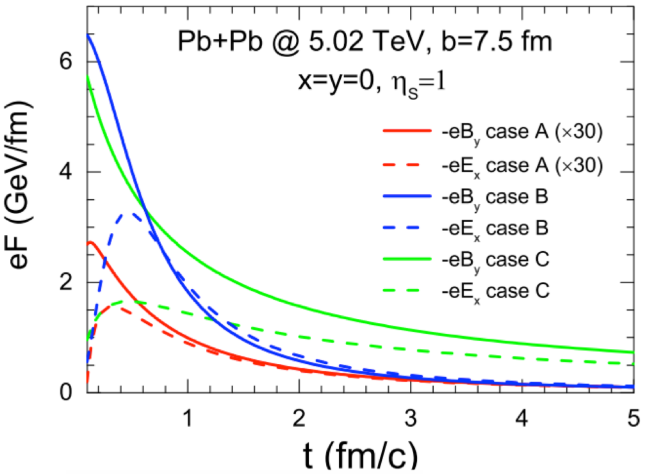




S. Shi et al., AP 394 (2018), 50-72
L. Mclerran et al., NPA 929 (2014) 184
G. Inghirami et al., EPJC 76 (2016), 659

❖ **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 σ_{el}? Early time what is σ_{el} in the Glasma?

Parametrized E.M. field



Sun&Plumari&Greco, PLB 816 (2021), 136271

Case A

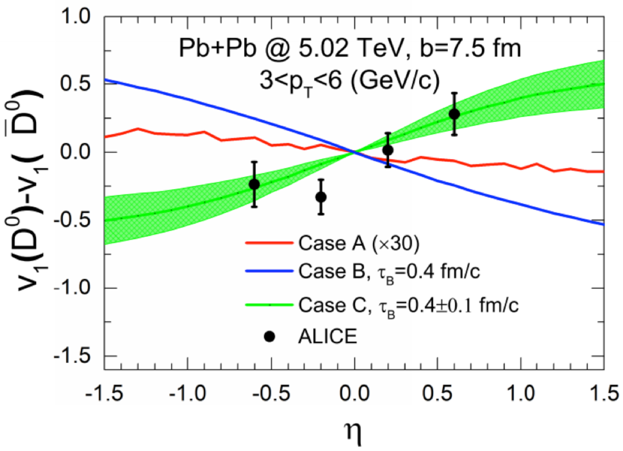
- ✓ E-B fields like U. Gursoy et al., PRC 89 (2014), 054905
- ✓ Medium at t<0 + eq. medium σ_{el}=0.023 fm^{-1}

Case B and C

$eB_y(x,y,\tau) = -B(\tau)\rho_B(x,y)$ $B(\tau) = eB_0/(1+(\tau/\tau_B)^a)$

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

- ✓ eB_0 fixed by the value t=0 in vaccum; a and τ_B can be tuned
- ✓ E_x is evaluated by the Faraday's Law



❖ **Case C** reproduces experimental data:

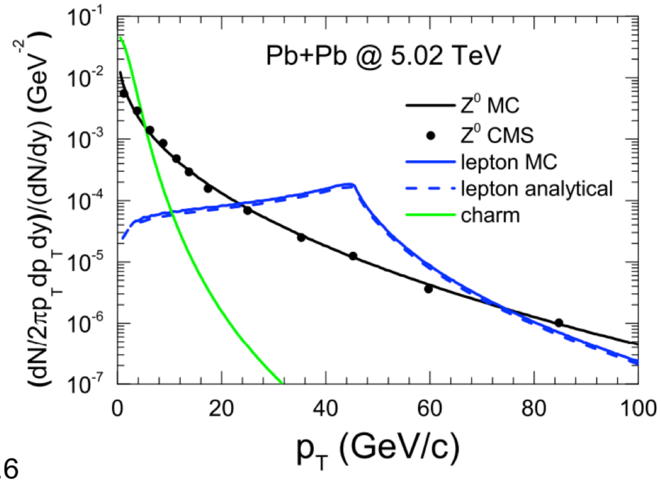
- ✓ Case B and Case C have the same τ_B and eB_0 but very different v_1 splitting
- ✓ **Constrain strongly the decay form of B_y(t)**: A slowly decay B leads to a relative smaller E, and B (Hall effect) wins over E

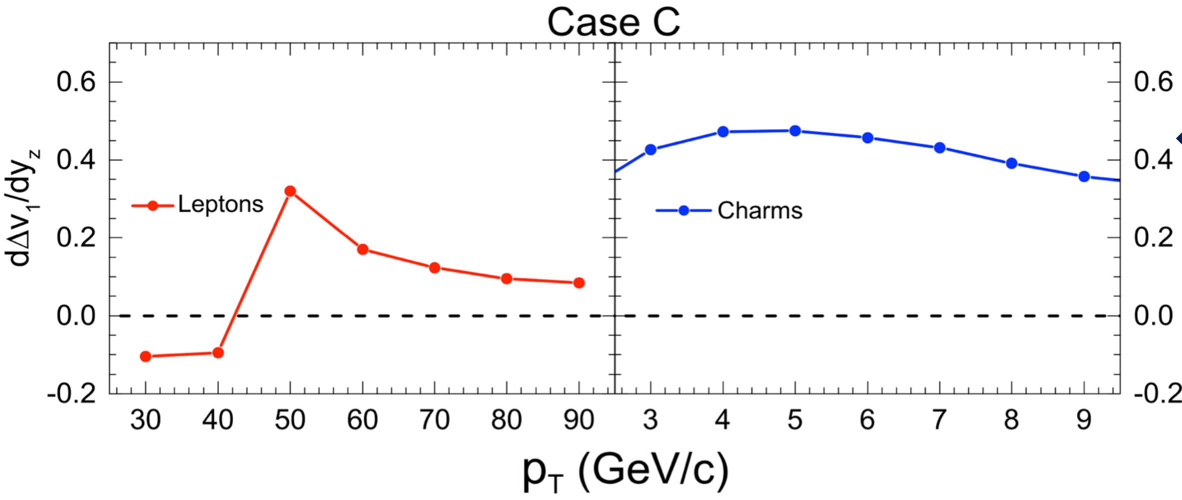
Leptons from Z^0 decay

❖ Leptons from Z^0 decay as a complementary probe:

- ✓ Clearer observables
- ✓ Separable from other sources
- ✓ $\tau_{decay}(Z^0) = \tau_{form}(\text{charm}) = 0.08$ fm/c→ Strong correlation between $\Delta v_1(D^0,\overline{D}^0)$ and $\Delta v_1(l^+,l^-)$

Sun&Plumari&Greco, PLB 816 (2021), 136271





❖ v_1 splitting of Z^0 decaying leptons **are quite different from** that of charm quarks:

- ✓ Sign change?
- ✓ Smaller magnitude (1e > 2/3e)?

$$\frac{d\Delta v_1^c}{dy_z}\Big|_{y_z=0} \propto -\alpha \frac{\partial \ln f_c}{\partial p_T}$$

The general behavior of charge dependent flows

induced by e.m. fields

General behavior of charge dependent flows by e.m. fields

$$
\begin{aligned}
f' &= f - \{\frac{\partial f(a_1+b_1)}{\partial p_T} + f(-\frac{p_T}{m_T^2}\frac{\partial(a_1+b_1)\tanh y_z}{\partial y_z} \\
&+ \frac{a_1+b_1}{p_T} + \frac{2}{m_T}\frac{\partial c_0/\cosh y_z}{\partial y_z})\} \\
&- \{-f\frac{p_T}{m_T^2}\frac{\partial(a_0+b_0)\tanh y_z}{\partial y_z} + \frac{\partial(a_0+b_0)f}{\partial p_T}\}\cos\phi \\
&- \sum_{n=1}\{\frac{\partial f(a_{n+1}+b_{n+1}+a_{n-1}-b_{n-1})}{\partial p_T} \\
&+ f[\frac{(n+1)(a_{n+1}+b_{n+1})-(n-1)(a_{n-1}-b_{n-1})}{p_T} \\
&- \frac{p_T}{m_T^2}\frac{\partial \tanh y_z(a_{n+1}+b_{n+1}+a_{n-1}-b_{n-1})}{\partial y_z} \\
&+ \frac{2}{m_T}\frac{\partial c_n/\cosh y_z}{\partial y_z}]\}\cos n\phi. \qquad (7)
\end{aligned}
$$

$$
\begin{aligned}
\overline{\Delta p_x} &= \sum 2a_n(p_T, y_z)\cos n\phi, \\
\overline{\Delta p_y} &= \sum 2b_n(p_T, y_z)\sin n\phi, \\
\overline{\Delta p_z} &= \sum 2c_n(p_T, y_z)\cos n\phi.
\end{aligned}
$$

- ✓ E.M. fields modify **spectra and charge dependent flow**
- ✓ The Lorentz force in **z direction also modifies** charge dependent flows as a azimuthal angle of transverse momentum

❖ The trajectory and the Lorentz force are same for quarks with p_T>>m
  - ✓ **p_T dependence is general and simple**

$$\frac{\partial a_n}{\partial p_T} \simeq 0, \frac{\partial b_n}{\partial p_T} \simeq 0, \frac{\partial c_n}{\partial p_T} \simeq 0 (p_T \gg m)$$

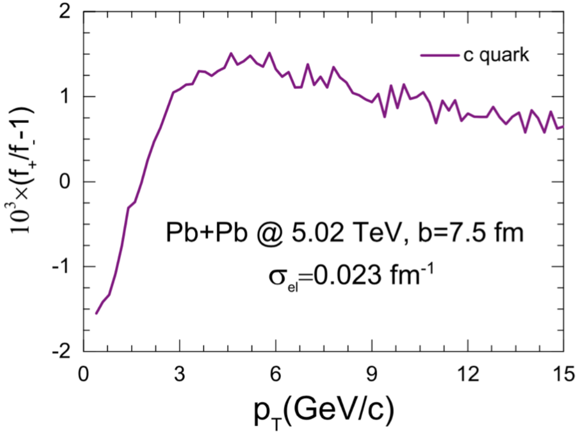
$$f' = f - \sum_{n=0}(d_n\frac{\partial f}{\partial p_T} + e_n\frac{f}{p_T})\cos n\phi \quad (p_T \gg m)$$

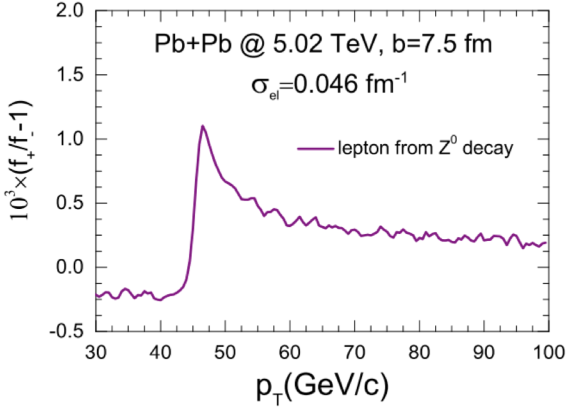
Sun&Greco &Plumari, EPJP 136 (2021), 726

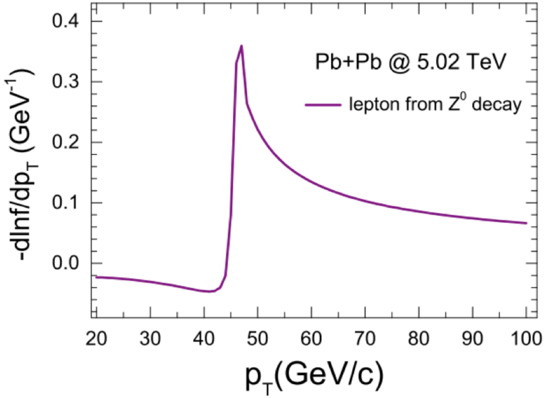
Spectra modification by e.m. fields

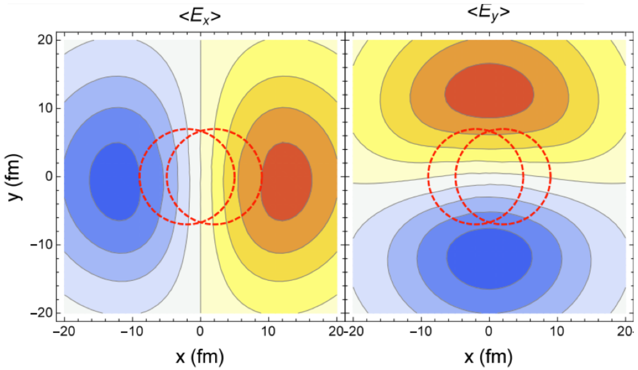
$$f'|_{y_z=0} = f\left[1-(a_1+b_1)\frac{\partial \ln f}{\partial p_T} - \frac{2}{p_T}\frac{\partial c_0}{\partial y_z}\right]|_{y_z=0}$$

Sun&Greco &Plumari, EPJP 136 (2021), 726









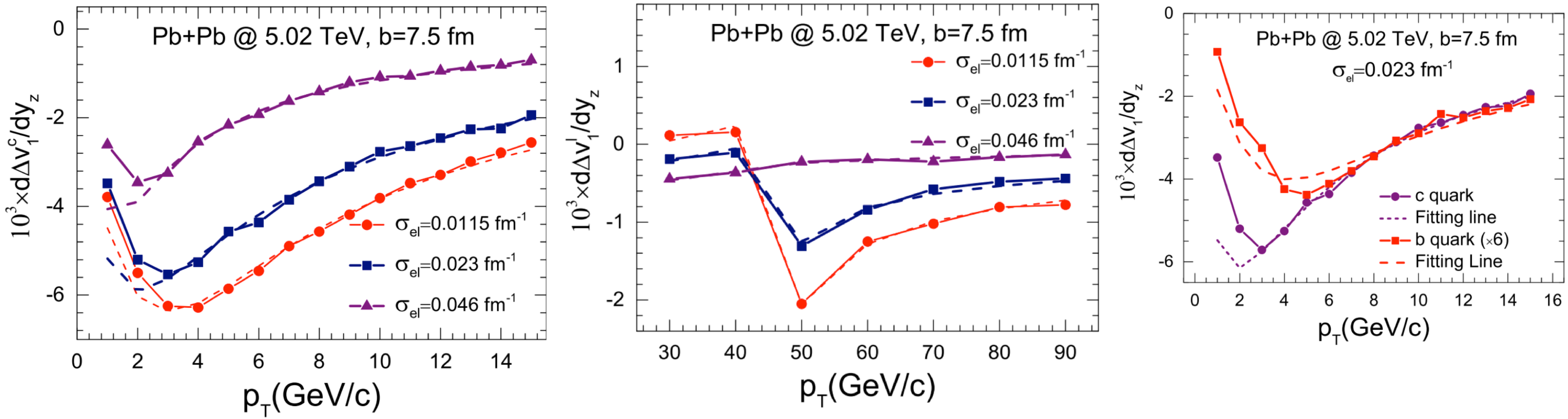
E.M. field of Case A

- ✓ The spectra modification by e.m. fields for charm and Z^0 decaying leptons **has a general p_T dependence**
- ✓ Spectra ratio probe **radical $\vec{r}$ dependence of electric field**

v_1 splitting by e.m. fields

$$\frac{d\Delta v_1^c}{dy_z}|_{y_z=0} = \frac{d\Delta a_0}{dy_z}|_{y_z=0}\left(-\frac{\partial \ln f_c}{\partial p_T} + \frac{2p_T}{m_T^2}\right) - \frac{1}{m_T}\left(\frac{d^2 c_1}{dy_z^2} - c_1\right) = -\alpha\frac{\partial \ln f_c}{\partial p_T} + (2\alpha - \beta)\frac{p_T}{m_T^2}$$

Sun&Greco &Plumari, EPJP 136 (2021), 726

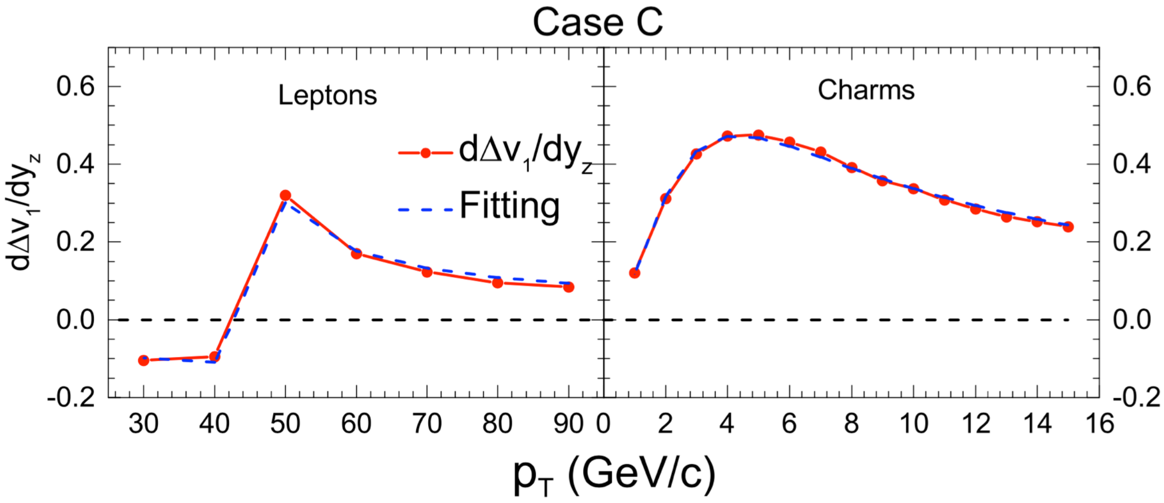


- ✓ The v_1 splitting by e.m. fields for charm, bottom and Z^0 decaying leptons **has a general p_T dependence**
- ✓ **low p_T derivation for charm quarks due to QGP interaction**

v_1 splitting by e.m. fields

$$\frac{d\Delta v_1^c}{dy_z}|_{y_z=0} = \frac{d\Delta a_0}{dy_z}|_{y_z=0}\left(-\frac{\partial \ln f_c}{\partial p_T}+\frac{2p_T}{m_T^2}\right)-\frac{1}{m_T}\left(\frac{d^2c_1}{dy_z^2}-c_1\right) = -\alpha\frac{\partial \ln f_c}{\partial p_T}+(2\alpha-\beta)\frac{p_T}{m_T^2}$$

Sun&Greco &Plumari, EPJP 136 (2021), 726



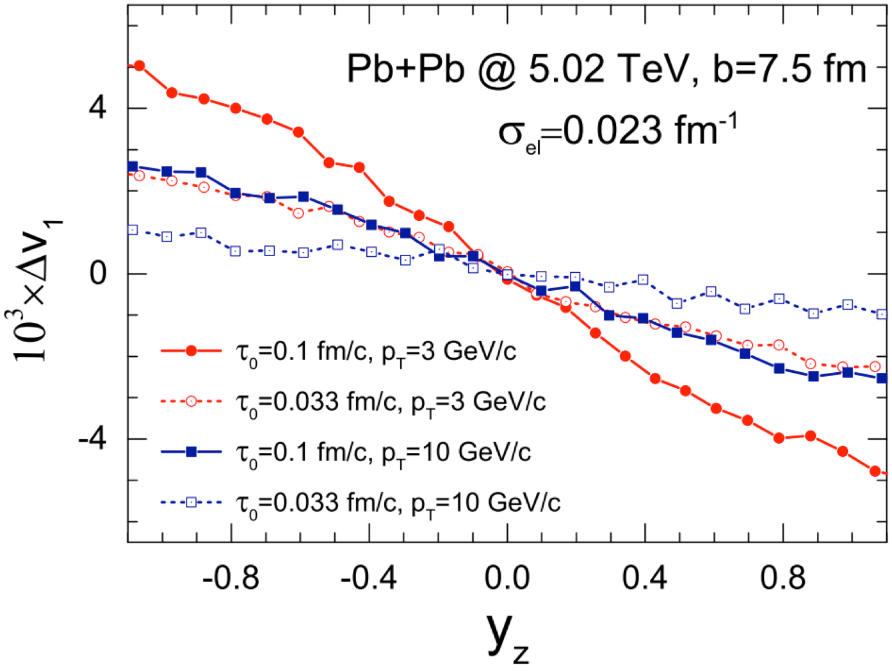
✓ p_T dependence of $d\Delta v_1$/dy applies to **different e.m. fields (Case A and Case C)**

Relation between α and B_y

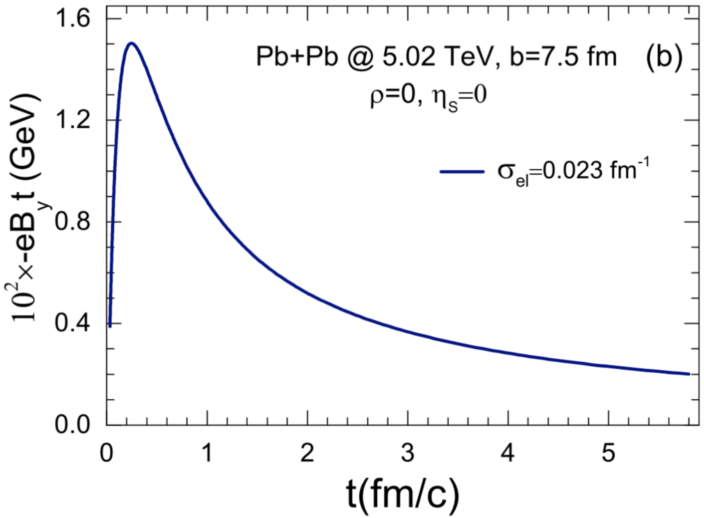
$$\frac{d\Delta v_1^c}{dy_z}|_{y_z=0} = \frac{d\Delta a_0}{dy_z}|_{y_z=0}\left(-\frac{\partial \ln f_c}{\partial p_T}+\frac{2p_T}{m_T^2}\right)-\frac{1}{m_T}\left(\frac{d^2c_1}{dy_z^2}-c_1\right) = -\alpha\frac{\partial \ln f_c}{\partial p_T}+(2\alpha-\beta)\frac{p_T}{m_T^2}$$

$$\alpha \simeq -|q|K\ \left[\tau_1 B_y(\tau_1,0)-\tau_0 B_y(\tau_0,0)\right]$$

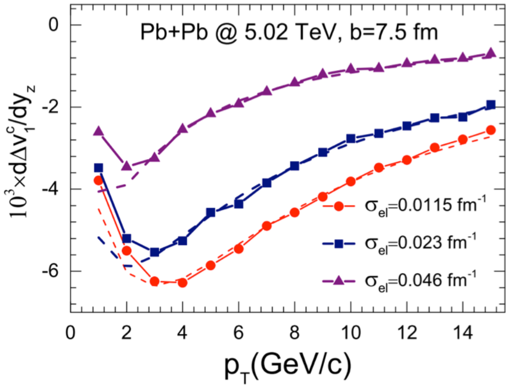
Sun&Greco &Plumari, EPJP 136 (2021), 726

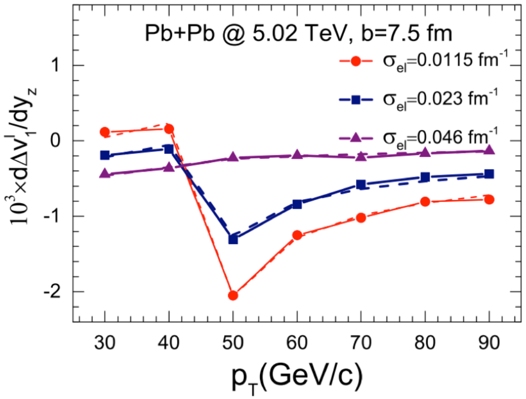


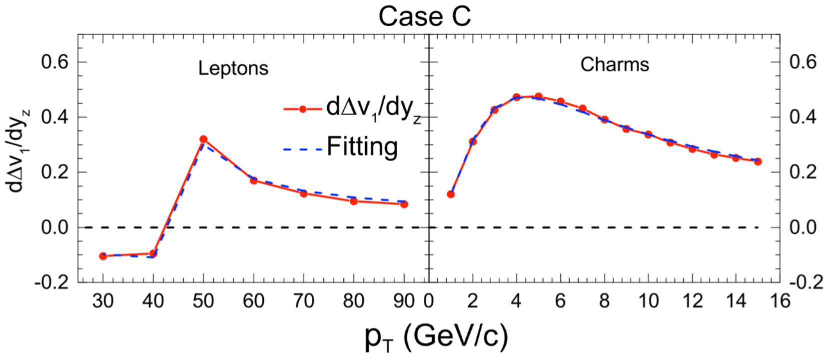
- ✓ **v_1 splitting probe tB_y varation**
- ✓ **Small change t_{form} changes significantly** v_1 splitting



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







Sun&Greco &Plumari, EPJP 136 (2021), 726

- ✓ α ratio for Case A with conductivity 0.0115, 0.023 fm^{-1} ~1.3-1.4, for Case C ~ 2, **close to their charge ratio 1.5 for very different e.m. fields: 100 times**
- ✓ Does not depend on the details of e.m. fields due to **same e.m. fields + similar formation time 0.08 fm/c + same space** of charm and these leptons
- ✓ Should **apply to all charge dependent flows + spectra ratio** (a_n,b_n,c_n)

Modification of Z^0 leptonic invariant mass by e.m. fields

E.m. fields on Z^0 leptonic invariant mass

- E.M. fields should **modify Z^0 leptonic invariant mass distribution** since it modify the momentum of leptons from Z^0 decay
- Measuring Z^0 leptonic invariant mass **may be easier than measuring the flows** of leptons from Z^0 decay

Sun&Greco&Wang, PLB 827, 136962 (2022)

❖ **Small effect of lepton-quarks scattering**

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

$$dp_i = -\gamma p_i dt + \xi_i\sqrt{2D_p dt},$$

$$D_p = \hat{q}/4$$

$$\hat{q} = \sum_q \int_{\mu^2}^{s^*/4} dq_\perp^2 \rho_q e_q^2 \frac{d\sigma}{dq_\perp^2} q_\perp^2 \qquad \frac{d\sigma}{dq_\perp^2} \approx e_q^2 \frac{2\pi\alpha_e^2}{q_\perp^4}$$

$$= \frac{12\zeta(3)}{\pi}\alpha_e^2 T^3 \ln\frac{s^*}{4\mu^2},$$

$$\mu^2 = \frac{1}{2}(3 + N_c\sum_q e_q^2)e^2T^2 = 10\pi\alpha_e T^2$$

✓ Modification on the leptonic invariant mass and its width are small

$$\Delta\langle M\rangle = -1.9 \text{ MeV and } \Delta\sigma \leq 0.2 \text{ MeV}$$

Mass	W: 80.379 ± 0.012 GeV/c^2[1] Z: 91.1876 ± 0.0021 GeV/c^2[2]
Decay width	W: 2.085 ± 0.042 GeV/c^2[1] Z: 2.4952 ± 0.0023 GeV/c^2[2]

✓ The invariant mass shift is negative due to the drag force

E.m. fields on Z^0 leptonic invariant mass

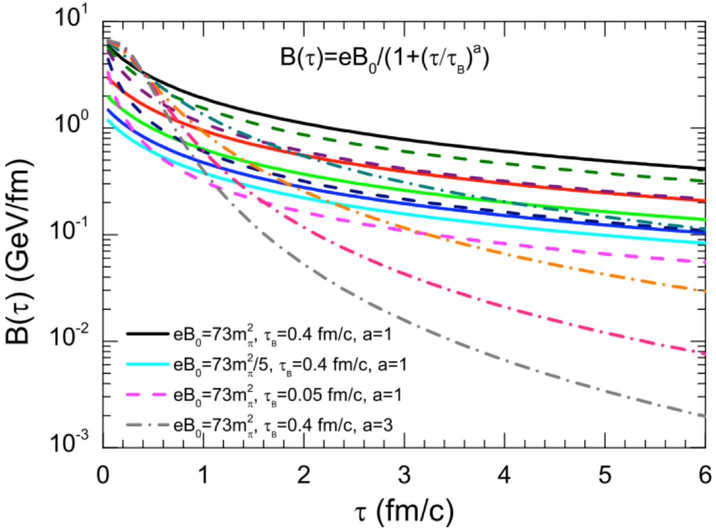
$$eB_y(x,y,\tau) = -B(\tau)\rho_B(x,y)$$

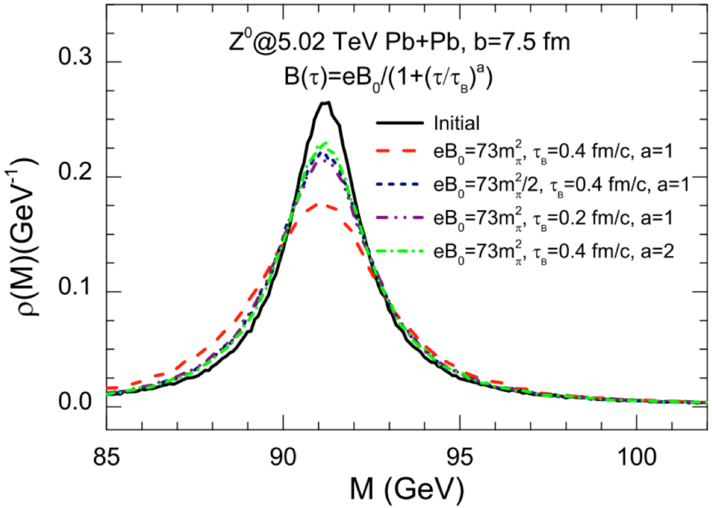
Sun&Greco&Wang, PLB 827, 136962 (2022)

$$\rho_B(x,y) = \exp[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}] \quad eE_x(t,x,y,\eta_S) = \rho_B(x,y)\int_0^{\eta_S} d\chi B'\left(\frac{t}{\cosh\chi}\right)\frac{t}{\cosh\chi}$$

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

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





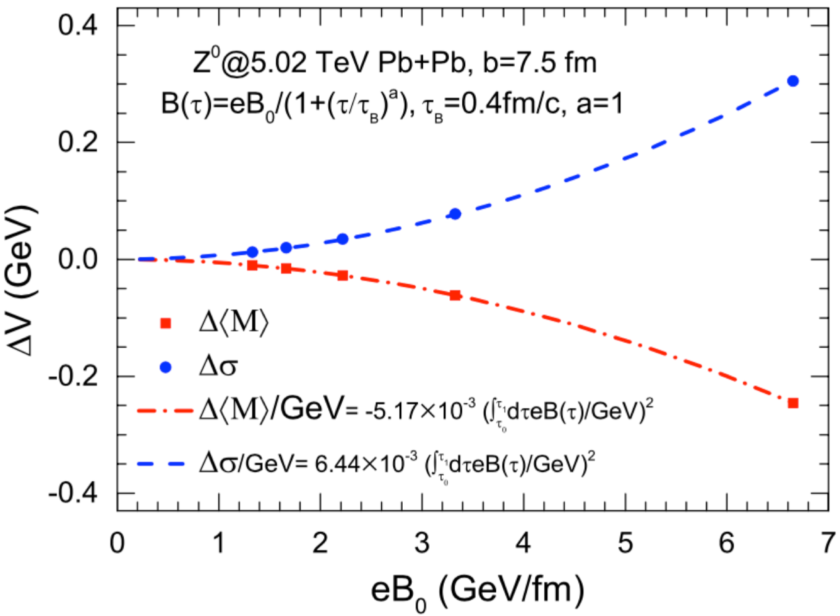
- ✓ eB_0 changes from $73m_\pi^2/5$ to $73m_\pi^2$
- ✓ τ_B changes from 0.05 fm/c to 0.4 fm/c
- ✓ a changes from 1 to 3

- ✓ The invariant mass **decreases~10 MeV-300 MeV**
- ✓ **The width increases**

The eB_0 dependence

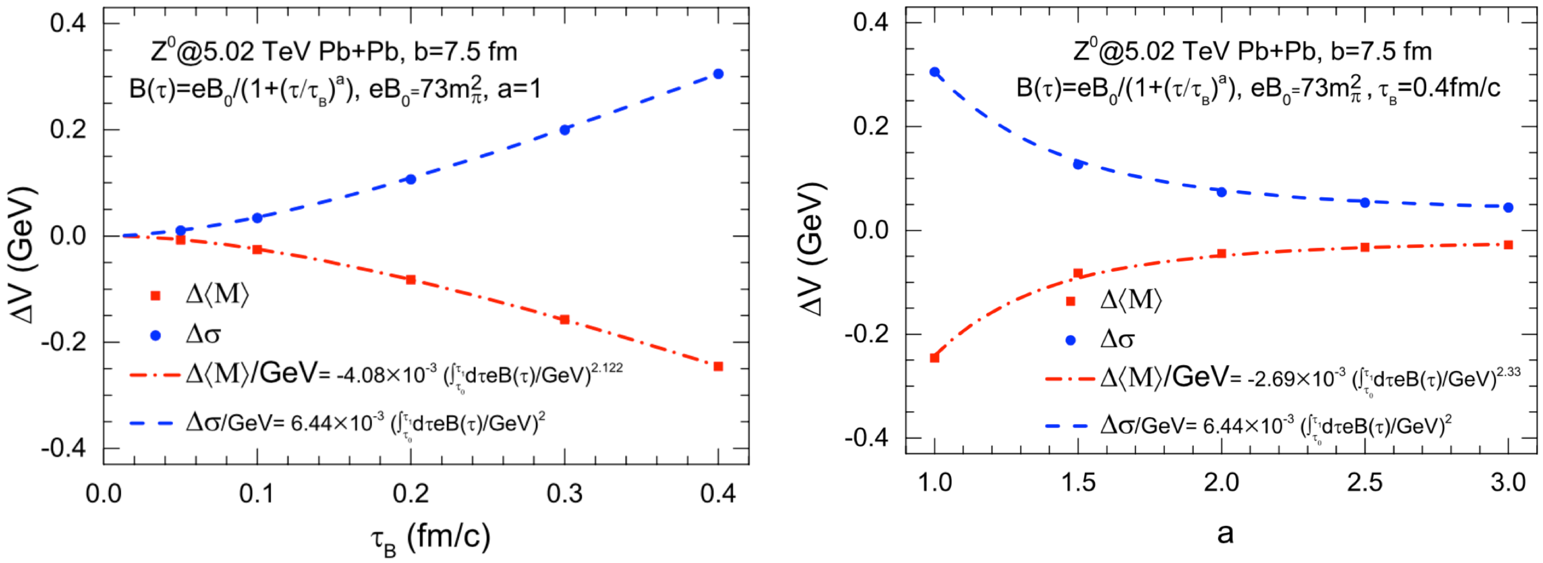
$$\Delta\langle M\rangle = \langle M_f\rangle - \langle M_i\rangle$$
$$\Delta\sigma = \sigma_f - \sigma_i$$
$$= \sqrt{\frac{\sum(M_f - \langle M_f\rangle)^2}{N-1}} - \sqrt{\frac{\sum(M_i - \langle M_i\rangle)^2}{N-1}}$$

Sun&Greco&Wang, PLB 827, 136962 (2022)



- ✓ The shift on the mean invariant mass and its width **should depend on eB_0 quadratically** due to charge conjugation invariant in the leading order
- ✓ **$(eB_0)^2$ dependence is perfectly fitted; -10 - -246 MeV and +12.6 - +305 MeV** shifts on mass and its width with eB_0 change by 5

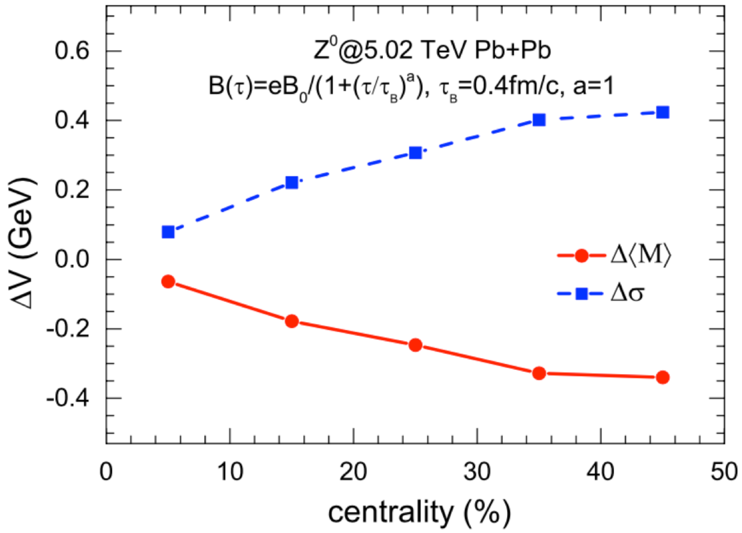
The τ_B and a dependence

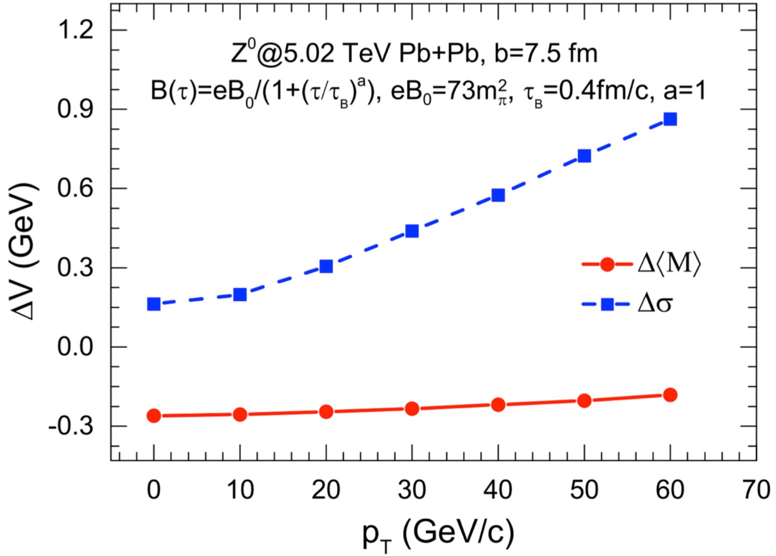


Sun&Greco&Wang, PLB 827, 136962 (2022)

- ✓ The shift on the mean invariant mass does not exactly depend on the integral of B_y quadratically **but approximately**
- ✓ The $(eB_0)^2$ dependence of **the width shift is still perfectly fitted quadratically**

The centrality and p_T dependence





Sun&Greco&Wang, PLB 827, 136962 (2022)

- ✓ Both shits **increase with centrality**
- ✓ **Increases less at centrality above 35%** since the range of e.m. fields decreases
- ✓ The invariant mass shift decreases with p_T but not much; **The width shift increases with p_T a lot**

Summary & outlook

- One can probe e.m. fields from v_1 splitting of charmed mesons and leptons from Z^0 decay
- Charge dependent flows and spectra modification induced by e.m. fields has a general p_T dependence
- The correlation between charge dependent flow of charmed mesons and leptons from Z^0 decay applies to all e.m. fields; strong indication of e.m. field origin
- The modification of Z^0 leptonic invariant mass and its width due to e.m. fields is another observable; depends on the integral of B_y quadratically (approximate)