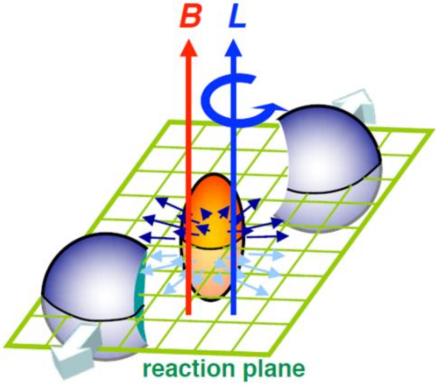
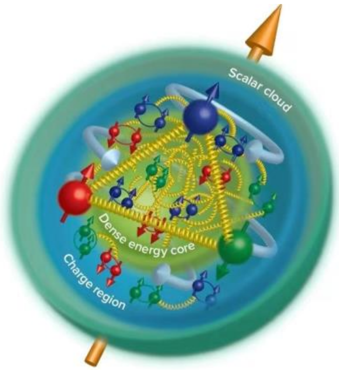




EM fields from the extended Kharzeev-McLerran-Warringa model and nucleon relativistic EM structures

Based on:
[YC, X.-L. Sheng & G.-L. Ma, NPA1011(2021)122199]
[YC, C. Lorcé, PRD106(2022)116024]
[YC, C. Lorcé, PRD107(2023)096003]

Yi Chen

thanks to:

Xin-Li Sheng, Guo-Liang Ma, Cédric Lorcé, Qun Wang

Department of Modern Physics,
University of Science and Technology of China

July 15-19, Chirality 2023 @UCAS

Outline

1. Introduction and motivations for strong EM fields

2. The extended KMW model for EM fields (part 1)

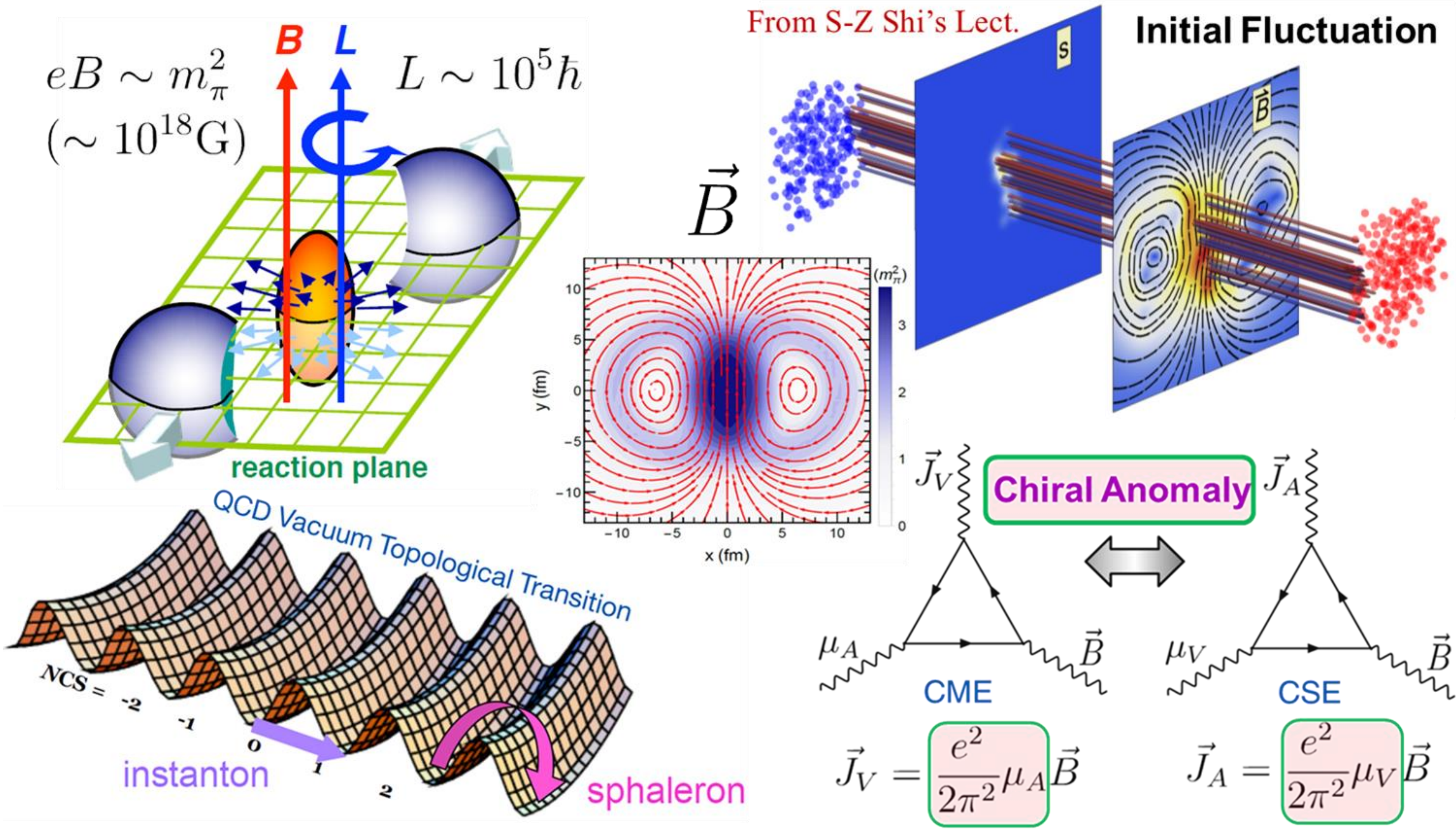
3. Nucleon relativistic EM structures (part 2)

4. Summary and outlook

†**KMW: Kharzeev-McLerran-Warringa**

Kharzeev, McLerran & Warringa, NPA 803 (2008) 227-253.

Motivations: Strong EM fields and their effects



$$\vec{J}_V = \boxed{\frac{e^2}{2\pi^2}\mu_A}\vec{B}$$

$$\vec{J}_A = \boxed{\frac{e^2}{2\pi^2}\mu_V}\vec{B}$$

$\mathcal{P}$ -odd

$\mathcal{C}$ -odd

Z.-T. Liang & X.-N. Wang, PRL94, 102301 (2005).
Kharzeev, McLerran & Warringa, NPA803 (2008).

Developments and many calculations on EM fields

Initial work on strong fields in HICs: From 1974 to 2008 (almost 32 years!)

Rafelski & B. Mueller (1976).

Liénard-Wiechert (L-W) equations of EM fields:

Skokov, Illarionov & Toneev (2009'); S. Voloshin (2010'); Voronyuk, et al. (2011'); L. Ou & B-A. Li (2011'); Bzdak & Skokov (2012'); Deng & Huang (2012'); Toneev et al.(2013,2014'); J. Bloczynski, X-G Hang, X. Zhao & J. Liao (2013'); Deng-Huang (2015'); V. Roy & S. Pu (2016'); X.-L. Zhao, G.-L. Ma & Y.-G. Ma (2018',2019'); Y.-L. Cheng, S. Zhang, Y.-G. Ma, et al.(2019'); J. Hammelmann, et al.(2020'); X.-G. Deng & Y.-G. Ma (2020'); Irfan, Sheng & Wang (2021'); ……

(Semi-) Analytic approaches:

Kharzeev, Mclerran & Warringa (2008'); Tuchin (2010', 2013', 2015', 2017', …); Asakawa (2010'); Liu & Greiner & Ko (2014'); Gürsoy & Kharzeev & Rajagopal (2014'); H. Li, X.-L. Sheng & Q. Wang (2016'); Hattori & Huang (2016); Gürsoy & Kharzeev & Marcus & Rajagopal & Shen (2018'); D. She & Feng & Zhong & Yin (2018'); Chen & Feng (2020'); Chen, Sheng & Ma (2021'); Grayson, Formanek, Rafelski & Mueller (2022); ……

Numerically solving Maxwell's equations (with Ohm conductivity):

Mclerran & Skokov (2014'); Zakharnov (2014'); Z. Wang, Zhao, Greiner, Xu & Zhuang (2022'); A. Huang, She, Shi, Huang & Liao (2023); H. Li, Xia, Huang & Huang (2023); ……

Magneto-hydrodynamics (considering QGP expansion and evolution):

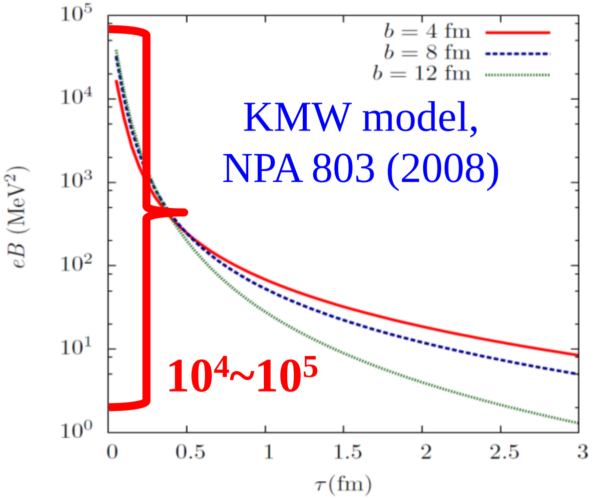
Gürsoy & Kharzeev & Rajagopal (2014'); Roy & Pu & Rezzolla & Rischke (2015'); Inghirami & Zanna, et al. (2016'); Gürsoy & Kharzeev & Marcus & Rajagopal & Shen (2018'); Dash, Shokri, Rezzolla, & Rischke (2023); ……

See, A. Dash's talk on July 18.

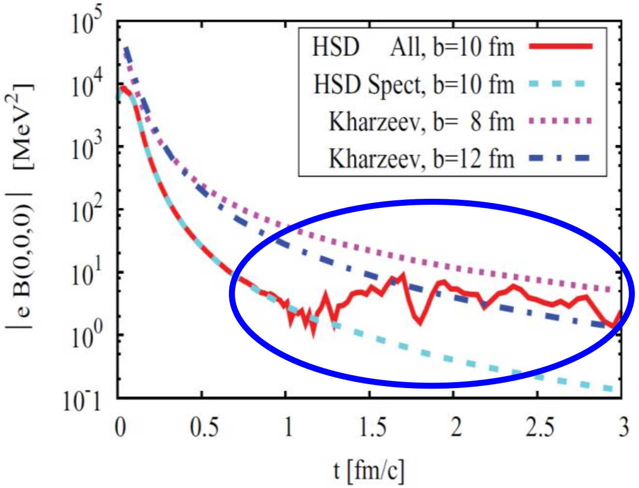
There are many theoretical efforts in the past 15 years for the calculations of EM fields.

(I sincerely apologize if I may have missed listing your works)

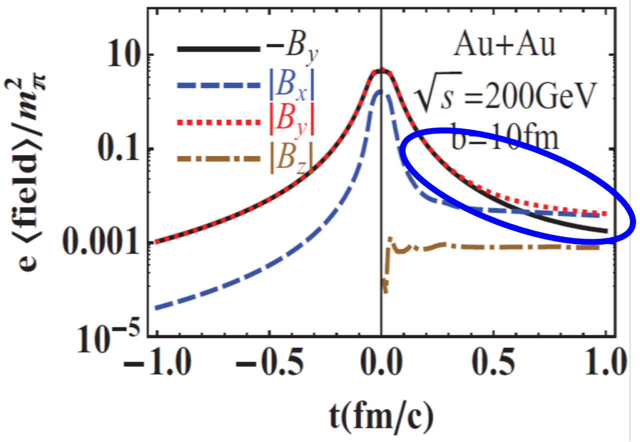
Time evolution of the strong magnetic field



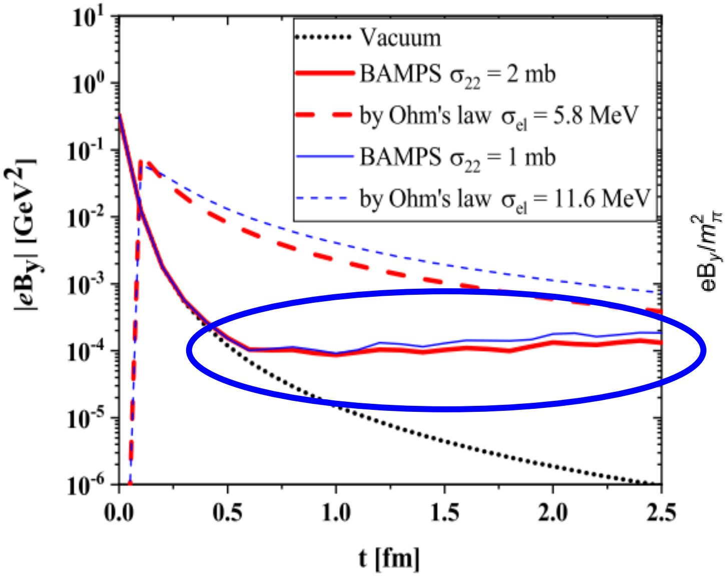
KMW model,
NPA 803 (2008)



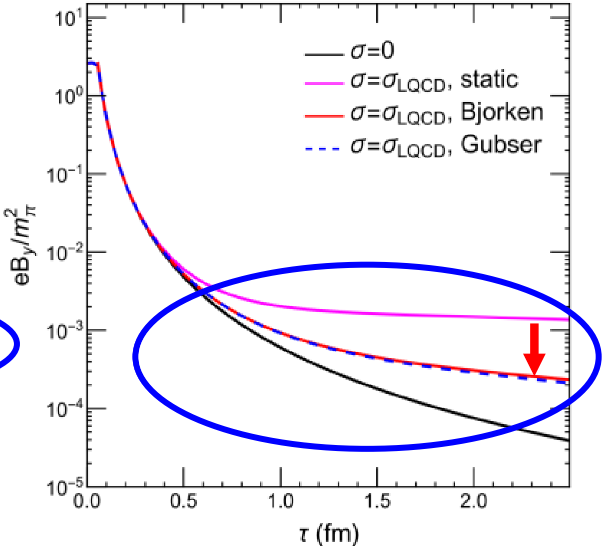
PHSD: PRC **83**, 054911 (2011)



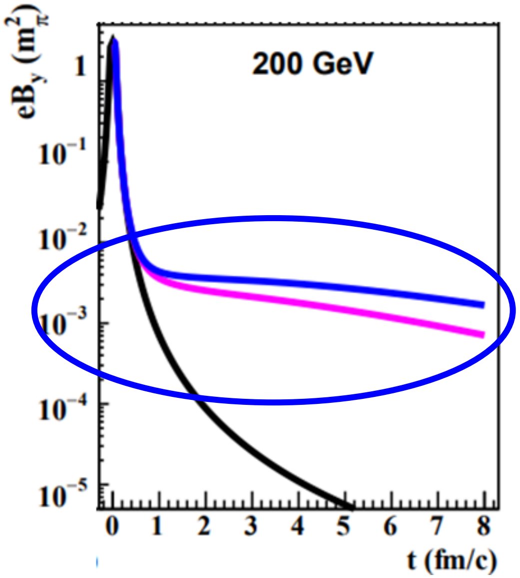
W.-T. Deng & X.-G. Huang (2012)



Wang, Zhao, Greiner, Xu & Zhuang,
PRC (2022)



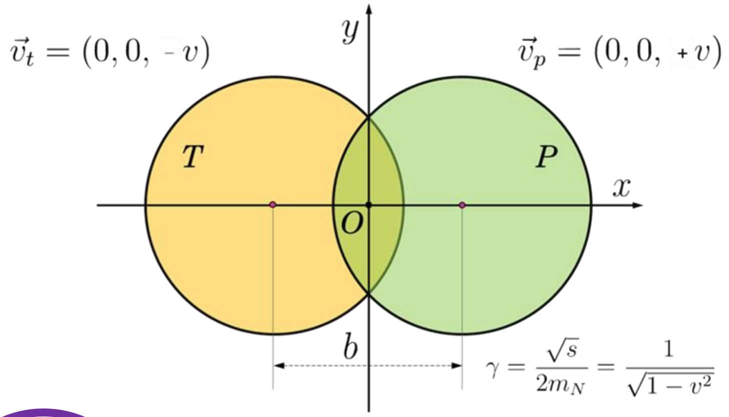
Huang, She, Shi, Huang & Liao
PRC (2023)



Li, Xia, Huang & Huang (2023)

The original KMW model

Decomposition of EM fields:



$$\vec{B} = \vec{B}_s^+ + \vec{B}_s^- + \vec{B}_p^+ + \vec{B}_p^-$$

$$\vec{E} = \vec{E}_s^+ + \vec{E}_s^- + \vec{E}_p^+ + \vec{E}_p^-$$

EM fields in the vacuum:

$$e\vec{B}_s^{\pm}(\tau,\eta,\vec{x}_\perp) = \pm Z\alpha_{\text{EM}} \sinh(Y_0 \mp \eta) \int \mathrm{d}^2\vec{x}'_\perp \boxed{\rho_\pm(\vec{x}'_\perp)} [1 - \theta_\mp(\vec{x}'_\perp)]$$
$$\times \frac{(\vec{x}'_\perp - \vec{x}_\perp) \times \vec{e}_z}{\left[(\vec{x}'_\perp - \vec{x}_\perp)^2 + \underline{\tau^2 \sinh(Y_0 \mp \eta)^2}\right]^{3/2}}$$

$$e\vec{B}_p^{\pm}(\tau,\eta,\vec{x}_\perp) = \pm Z\alpha_{\text{EM}} \int \mathrm{d}^2\vec{x}'_\perp \int_{-Y_0}^{Y_0} \mathrm{d}Y f(Y) \sinh(Y \mp \eta) \boxed{\rho_\pm(\vec{x}'_\perp)} \theta_\mp(\vec{x}'_\perp)$$
$$\times \frac{(\vec{x}'_\perp - \vec{x}_\perp) \times \vec{e}_z}{\left[(\vec{x}'_\perp - \vec{x}_\perp)^2 + \underline{\tau^2 \sinh(Y \mp \eta)^2}\right]^{3/2}}$$

Kharzeev, McLerran & Warringa, NPA 803 (2008) 227-253.

The original KMW model

Widely used L-W formula:

See, part 2. ↑

"Singularity" problem

$$eE(t,\boldsymbol{r}) = \alpha_{\mathrm{EM}} \sum_{n=\pm} Z_n \frac{\boldsymbol{R}_n\left(1 - v_n^2\right)}{\left(R_n^2 - \left[\boldsymbol{v}_n \times \boldsymbol{R}_n\right]^2\right)^{3/2}},$$

$$eB(t,\boldsymbol{r}) = \alpha_{\mathrm{EM}} \sum_{n=\pm} Z_n \frac{\boldsymbol{v}_n \times \boldsymbol{R}_n\left(1 - v_n^2\right)}{\left(R_n^2 - \left[\boldsymbol{v}_n \times \boldsymbol{R}_n\right]^2\right)^{3/2}},$$

$$\Rightarrow \begin{cases} \lim\limits_{R_n \to 0} e\vec{E} = +\infty \\ \lim\limits_{R_n \to 0} e\vec{B} = +\infty \end{cases}$$

δ-functions: $\rho_n(t,\boldsymbol{r}') = Q\delta^{(3)}(\boldsymbol{r}') = Ze\underline{\delta(x')\delta(y')\delta(z' - z'_n \mp |\boldsymbol{v}_n|t)}$

In terms of rapidity: *Y* ↓

$$eE(t,\boldsymbol{r}) = \alpha_{\mathrm{EM}} \sum_{n=\pm} \frac{Z_n \cosh(Y_n) \cdot \boldsymbol{R}_n}{\left\{(x - x'_n)^2 + (y - y'_n)^2 + \left[t \sinh Y_n - (z - \boxed{z'_n}) \cosh Y_n\right]^2\right\}^{3/2}},$$

$$eB(t,\boldsymbol{r}) = \alpha_{\mathrm{EM}} \sum_{n=\pm} \frac{Z_n \sinh(Y_n) \cdot \boldsymbol{e}_z \times \boldsymbol{R}_n}{\left\{(x - x'_n)^2 + (y - y'_n)^2 + \left[t \sinh Y_n - (z - \boxed{z'_n}) \cosh Y_n\right]^2\right\}^{3/2}}.$$

YC, X.-L. Sheng & G.-L. Ma, NPA 1011 (2021) 122199.

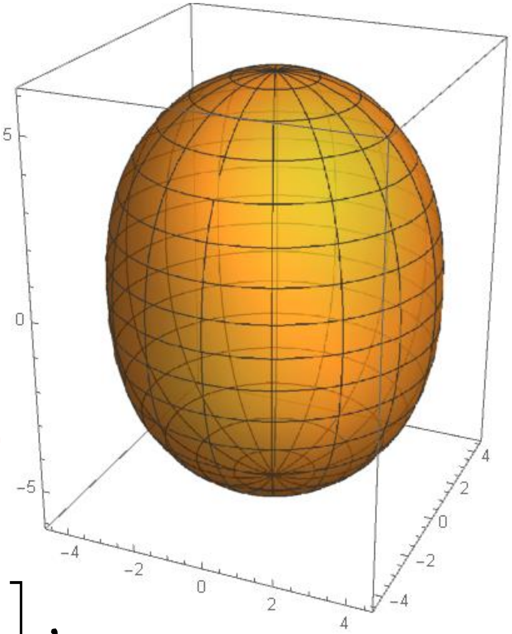
Possible extensions: I

Generalized charge distributions (with Lorentz contraction effect):

$$\rho(\boldsymbol{r}') = \gamma\rho_0 \frac{1+\omega\left[r'/R'(\theta,\phi)\right]^2}{1+\exp\left\{\left[r'-R'(\theta,\phi)\right]/d\right\}}\Theta(\boldsymbol{r}'),$$

$$r' = r'(\gamma) \equiv \sqrt{\boldsymbol{r}'^{\,2}_{\perp} + (\gamma z')^2},$$

E.g., U, Zr,…

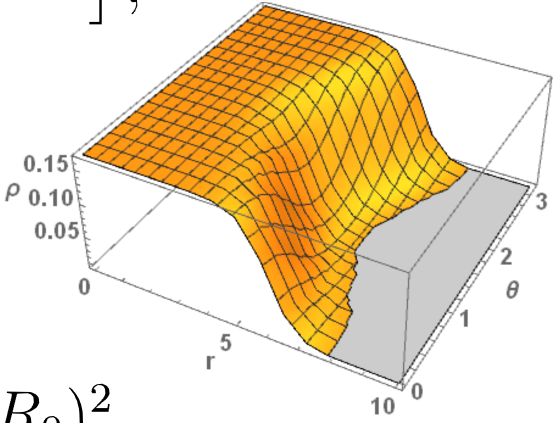


Axial deformation:

$$R' = R'(\theta,\phi) \equiv R_0\left[1+\beta_2 Y_2^0(\theta)+\beta_4 Y_4^0(\theta)+\cdots\right],$$

Normalization:

$$Z = \int_{-R_A}^{+R_A}\mathrm{d}x'\int_{-R_A}^{+R_A}\mathrm{d}y'\int_{-R_A/\gamma}^{+R_A/\gamma}\mathrm{d}z'\,\rho(\boldsymbol{r}'),$$



Spherically symmetric:

$$\rho(\boldsymbol{r}') = \gamma\rho_0 \frac{1+\omega(r'/R_0)^2}{1+\exp\left[\left(r'-R_0\right)/d\right]}\Theta(\boldsymbol{r}').$$

Possible extensions: II

Baryon-junction stopping effect: $\alpha_y \sim$ Regge trajectory intercept.

$$f_{\pm}(Y) = \frac{\alpha_y}{2\sinh(\alpha_y Y_0)} e^{\pm\alpha_y Y}, \ -Y_0 \le Y \le Y_0$$

See, Prof. Zhangbu Xu's talk on July 18.

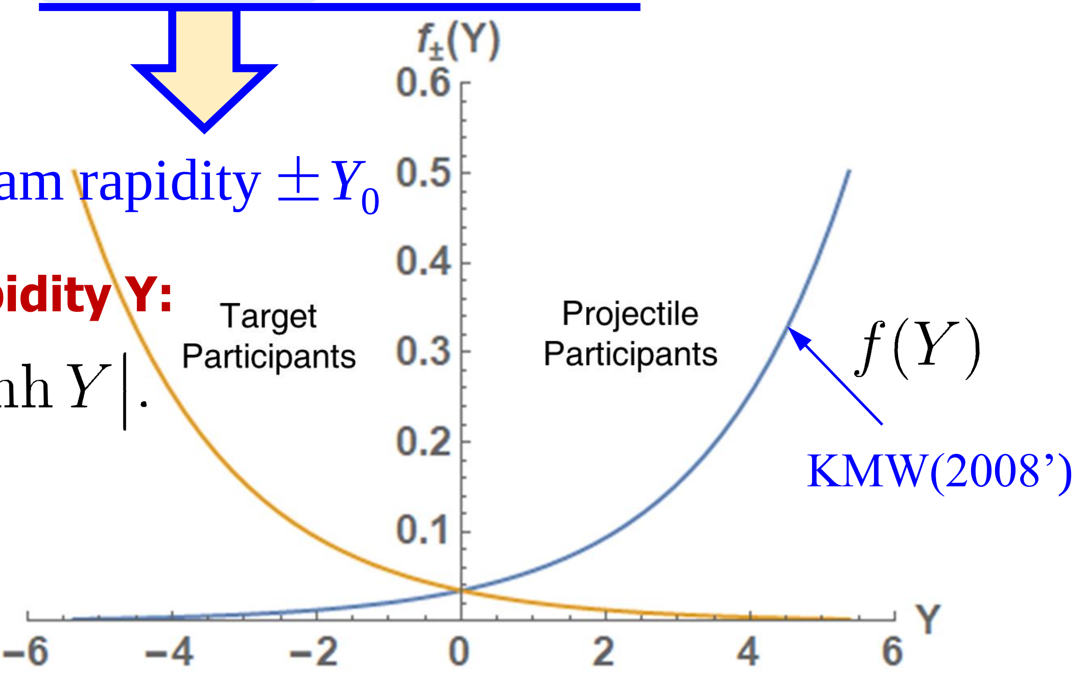
Refined Baryon-junction stopping effects with retardation correction (w/ RC)

$$\Psi_{\pm}(Y) = \underbrace{\theta(t_{\text{ret}} - t_c) \cdot f_{\pm}(Y)} + \underbrace{\theta(t_c - t_{\text{ret}}) \cdot \delta(Y \mp Y_0)}.$$

normalized $f_{\pm}(Y)$ beam rapidity $\pm Y_0$

Retardation relation for each rapidity Y:

$$t_{\text{ret}} = t - \left| \boldsymbol{r} - \boldsymbol{r}' - t_{\text{ret}} \cdot \boldsymbol{e}_z \tanh Y \right|.$$



KMW, NPA 803 (2008) 227-253.
ALICE, EPJC 73, 2496 (2013);
Gürsoy & Kharzeev & Marcus & Rajagopal & Shen (2018');

The extended KMW model: vacuum case

Contributions of spectators:

$$e\boldsymbol{E}^{\pm}_{\mathrm{S}}(t,\boldsymbol{r}) = \alpha_{\mathrm{EM}}\cosh(Y_0)\int_{V_\pm}\mathrm{d}^3\boldsymbol{r}'\,\frac{\boxed{\rho_\pm(\boldsymbol{r}')}\left[1-\tilde{\Theta}_\mp(\boldsymbol{r}'_\perp)\right]\boldsymbol{R}_\pm}{\left\{(\boldsymbol{r}_\perp-\boldsymbol{r}'_\perp)^2+\left[t\sinh(\pm Y_0)-(z-z')\cosh Y_0\right]^2\right\}^{3/2}},$$

$$e\boldsymbol{B}^{\pm}_{\mathrm{S}}(t,\boldsymbol{r}) = \alpha_{\mathrm{EM}}\sinh(\pm Y_0)\int_{V_\pm}\mathrm{d}^3\boldsymbol{r}'\,\frac{\boxed{\rho_\pm(\boldsymbol{r}')}\left[1-\tilde{\Theta}_\mp(\boldsymbol{r}'_\perp)\right]\boldsymbol{e}_z\times\boldsymbol{R}_\pm}{\left\{(\boldsymbol{r}_\perp-\boldsymbol{r}'_\perp)^2+\left[t\sinh(\pm Y_0)-(z-z')\cosh Y_0\right]^2\right\}^{3/2}},$$

Contributions of participants:

$$e\boldsymbol{E}^{\pm}_{\mathrm{P}}(t,\boldsymbol{r}) = \alpha_{\mathrm{EM}}\int_{V_\pm}\mathrm{d}^3\boldsymbol{r}'\int_{-Y_0}^{Y_0}\mathrm{d}Y\,\frac{\Psi_\pm(Y)\cosh Y\cdot\boxed{\rho_\pm(\boldsymbol{r}')}\tilde{\Theta}_\mp(\boldsymbol{r}'_\perp)\boldsymbol{R}_\pm}{\left\{(\boldsymbol{r}_\perp-\boldsymbol{r}'_\perp)^2+\left[t\sinh Y-(z-z')\cosh Y\right]^2\right\}^{3/2}},$$

$$e\boldsymbol{B}^{\pm}_{\mathrm{P}}(t,\boldsymbol{r}) = \alpha_{\mathrm{EM}}\int_{V_\pm}\mathrm{d}^3\boldsymbol{r}'\int_{-Y_0}^{Y_0}\mathrm{d}Y\,\frac{\Psi_\pm(Y)\sinh Y\cdot\boxed{\rho_\pm(\boldsymbol{r}')}\tilde{\Theta}_\mp(\boldsymbol{r}'_\perp)\boldsymbol{e}_z\times\boldsymbol{R}_\pm}{\left\{(\boldsymbol{r}_\perp-\boldsymbol{r}'_\perp)^2+\left[t\sinh Y-(z-z')\cosh Y\right]^2\right\}^{3/2}},$$

YC, X.-L. Sheng & G.-L. Ma, NPA 1011 (2021) 122199.

The extended KMW model: QGP evolution (mixed) case

Time-dependent Ohm conductivity during the QGP evolution:

$$\sigma \to \tilde{\sigma}(t) = \sigma_0 \cdot \theta(t - t_\sigma),$$

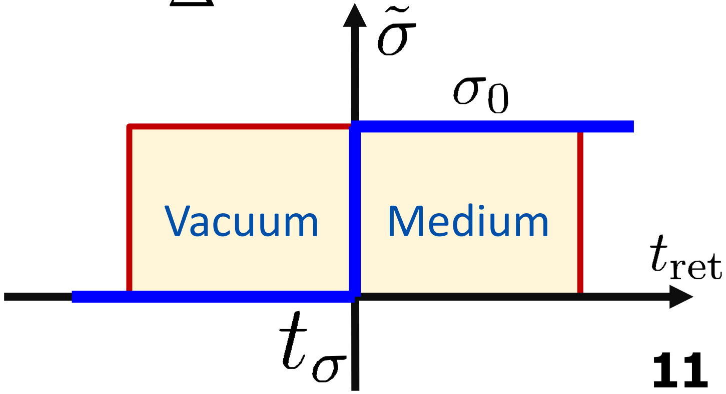
$\sigma_0 \approx 5.8\,\mathrm{MeV}$ (LQCD)

$t_\sigma \sim$ Medium time

Contributions of spectators & participants:

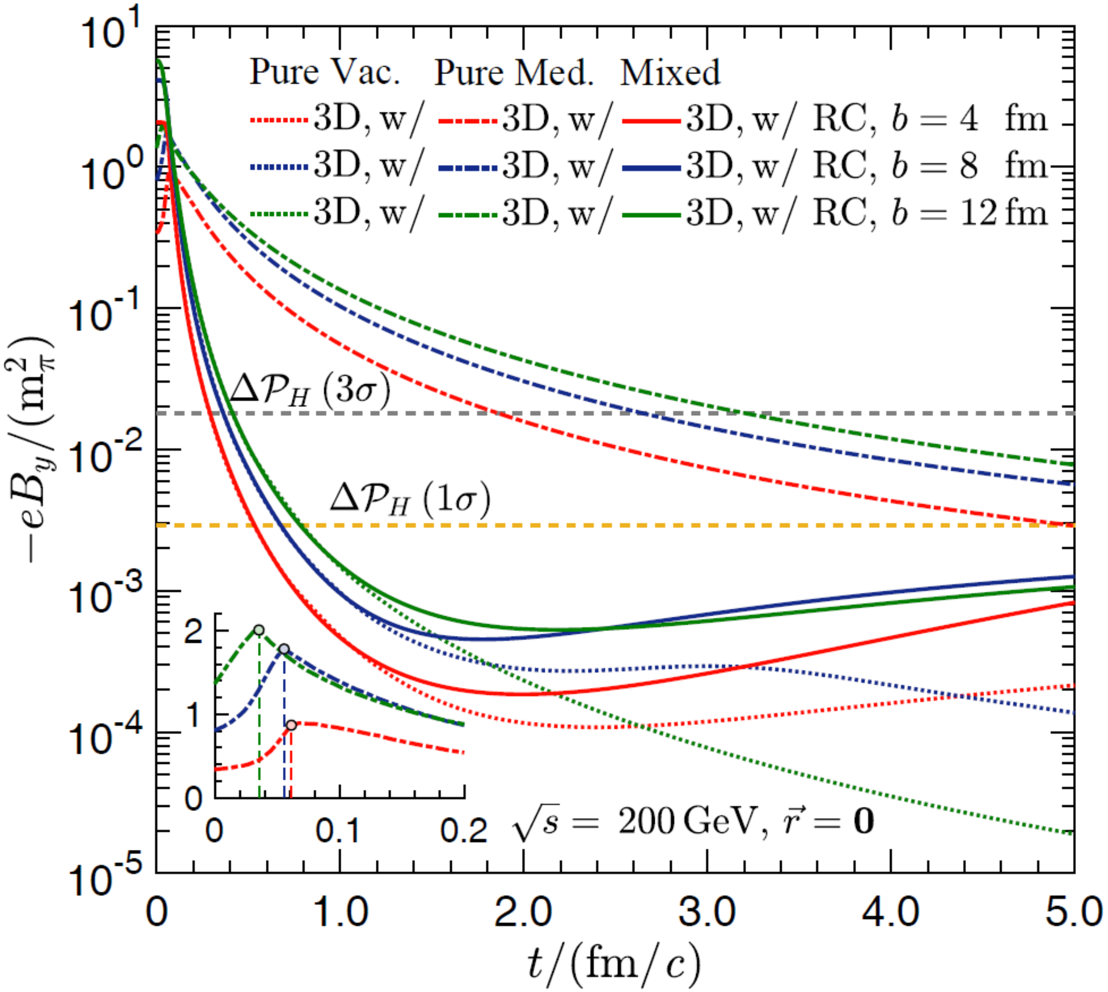
$$e\boldsymbol{B}_{\mathrm{S}}^{\pm}(t,\boldsymbol{r}) = \lim_{Y\to\pm Y_0} \alpha_{\mathrm{EM}} \sinh Y \int_{V_\pm} \mathrm{d}^3\boldsymbol{r}'\, \frac{\rho_\pm(\boldsymbol{r}')\left[1-\tilde{\Theta}_\mp(\boldsymbol{r}'_\perp)\right]\boldsymbol{e}_z \times \boldsymbol{R}_\pm}{\Delta^{3/2}} \times \left[1 + \frac{\tilde{\sigma}(t_{\mathrm{ret}})\sinh|Y|}{2}\sqrt{\Delta}\right] e^{\tilde{A}},$$

$$e\boldsymbol{B}_{\mathrm{P}}^{\pm}(t,\boldsymbol{r}) = \alpha_{\mathrm{EM}} \int_{V_\pm} \mathrm{d}^3\boldsymbol{r}' \int_{-Y_0}^{Y_0} \mathrm{d}Y\, \frac{\Psi_\pm(Y)\sinh Y \cdot \rho_\pm(\boldsymbol{r}')\tilde{\Theta}_\mp(\boldsymbol{r}'_\perp)\boldsymbol{e}_z \times \boldsymbol{R}_\pm}{\Delta^{3/2}} \times \left[1 + \frac{\tilde{\sigma}(t_{\mathrm{ret}})\sinh|Y|}{2}\sqrt{\Delta}\right] e^{\tilde{A}}.$$



H. Li, X.-L. Sheng & Q. Wang PRC (2017).
YC, X.-L. Sheng & G.-L. Ma, NPA 1011 (2021) 122199.
H. Li, X. Xia, X.-G. Huang & H.-Z. Huang (2023)

Results from the extended KMW model



$$e|B| = \frac{eT_s|\Delta\mathcal{P}_H|}{2|\mu_\Lambda|}$$

$$\Delta\mathcal{P} = \mathcal{P}_\Lambda - \mathcal{P}_{\bar{\Lambda}}$$

$T_s \sim$ Thermal freeze-out temperature(~150 MeV)

$$\mu_\Lambda = -\mu_{\bar{\Lambda}} = -0.613\mu_N$$

STAR Coll.

$1\sigma,\ 3\sigma$ constraints from Λ and $\bar{\Lambda}$ polarizations

$t_s \sim$ hydrodynamic thermal freeze-out time.

$t_s \simeq 5\,\mathrm{fm}/c$ **(Hydro)**

$\sigma_0 \approx 5.8\,\mathrm{MeV}$ **(LQCD)**

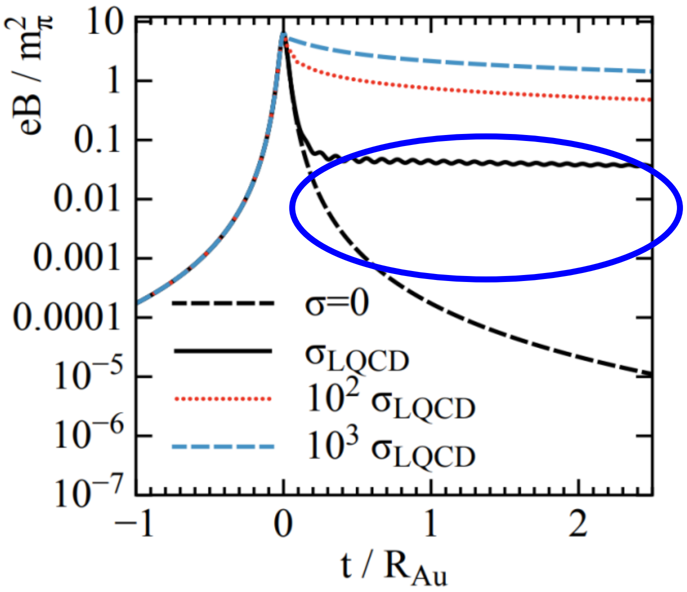
Becattini, Karpenko, Lisa, Upsal, & Voloshin, PRC (2017).

STAR paper, PRC 98, 014910 (2018).

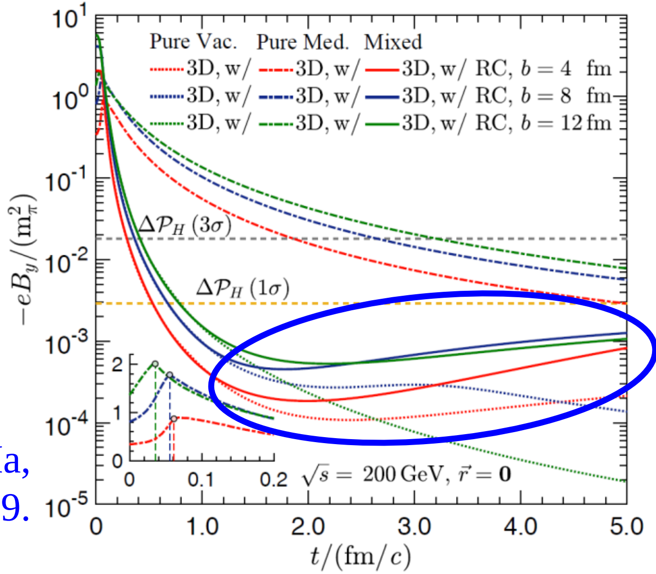
Müller & Schäfer, PRD 98, 071902(R) (2018).

Guo, Shi, Feng & Liao, PLB 798 (2019) 134929.

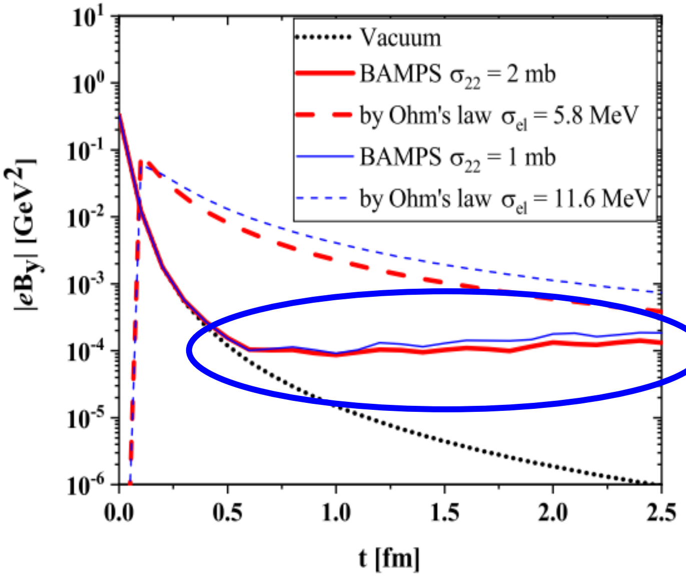
Time evolution of the strong magnetic field

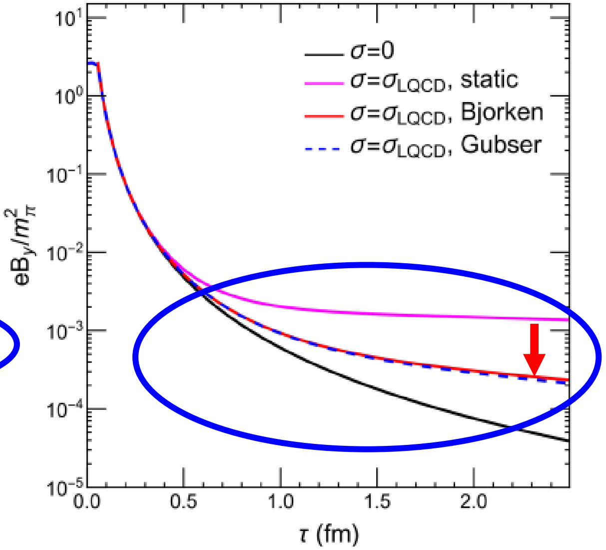


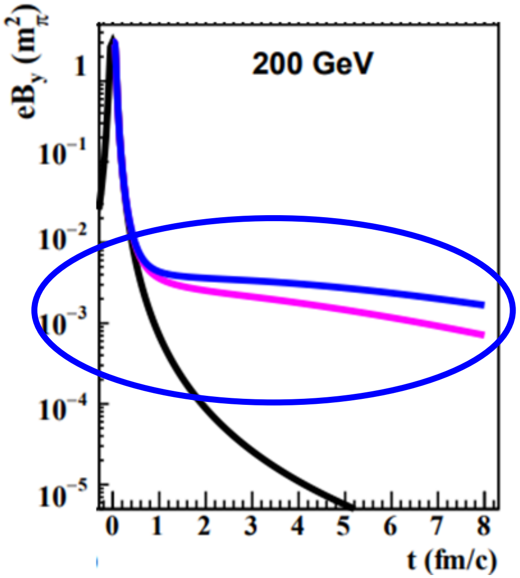
Mclerran-Skokov, NPA 929 (2014) 184-190.



YC, X.-L. Sheng & G.-L. Ma, NPA 1011 (2021) 122199.





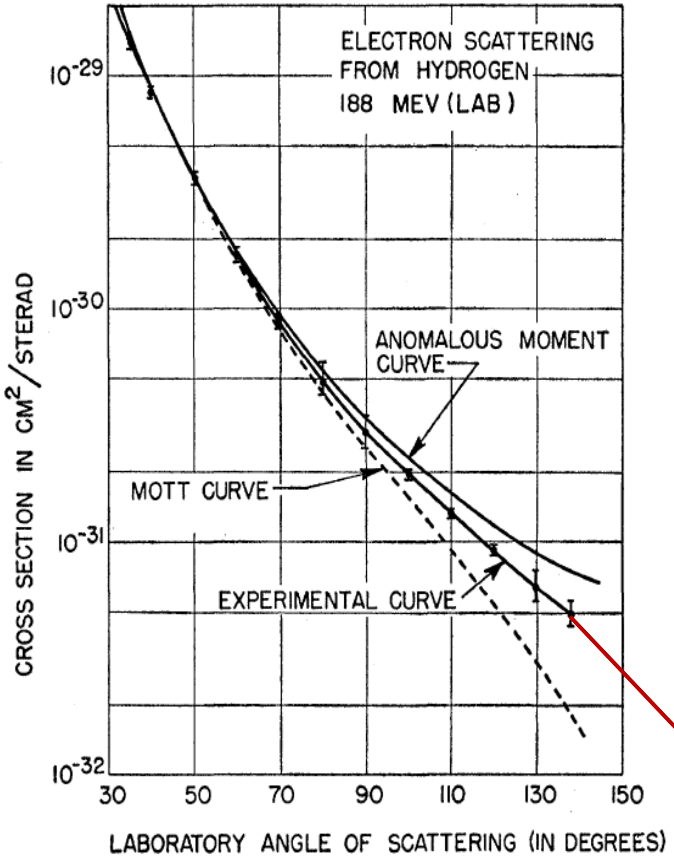


Wang, Zhao, Greiner, Xu & Zhuang, PRC (2022)

Huang, She, Shi, Huang & Liao PRC (2023)

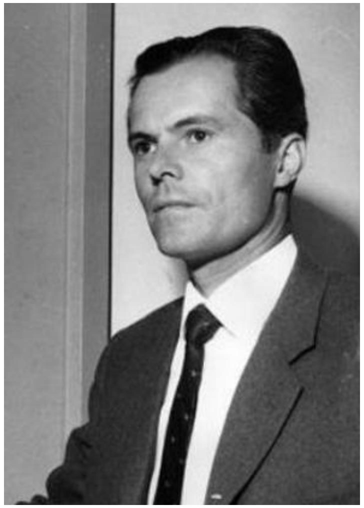
Li, Xia, Huang & Huang (2023)

Elastic e-N scattering



Nobel prize in physics (1961)

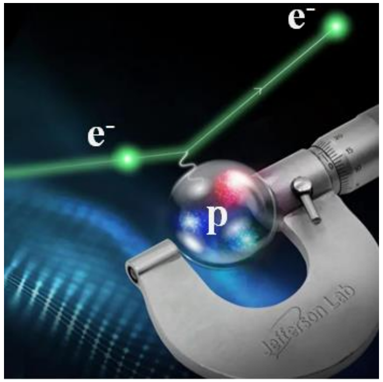
Robert Hofstadter



Rudolf Mössbauer

Nucleon is not a point-like particle! It has clear meaningful structures, known as EM form factors.

$$r_E^p \approx 0.78\ \mathrm{fm}$$



Robert Hofstadter and Robert W. Mcallister. "Electron Scattering from the Proton" Phys. Rev. 98, 217 (1955).

W. Xiong et al. (PRad), Nature (London) 575, 147 (2019).

$$r_E^p \approx 0.831\ \mathrm{fm}$$

Nucleon relativistic EM four-current distributions

* **Increasing spin will increase the complexity of a system.**

See, Prof. Yang Li's talk on July 19.

- **BF distributions (3D):**

$$\frac{1}{\sqrt{1+\tau}} \approx 1 - \boxed{\frac{\tau}{2}} + \cdots$$

Darwin-Foldy term

Foldy and Wouthuysen, PR 78, 29(1950).

$$J^0_B(\boldsymbol{r}) = e\delta_{s's} \int \frac{\mathrm{d}^3\Delta}{(2\pi)^3} e^{-i\boldsymbol{\Delta}\cdot\boldsymbol{r}} \boxed{\frac{M}{P^0_B}} G_E(\boldsymbol{\Delta}^2),$$

$$\boldsymbol{J}_B(\boldsymbol{r}) = e\frac{\boldsymbol{\nabla}\times\boldsymbol{\sigma}_{s's}}{2M} \int \frac{\mathrm{d}^3\Delta}{(2\pi)^3} e^{-i\boldsymbol{\Delta}\cdot\boldsymbol{r}} \frac{M}{P^0_B} G_M(\boldsymbol{\Delta}^2)$$

- **Poincaré symmetry:**

[Durand, Celles & Marr, PR126 (1962) 1882]

$$\langle p', s'|\hat{j}^\mu(0)|p, s\rangle = \sum_{s'_B, s_B} \underbrace{D^{\dagger(j)}_{s's'_B}(p'_B,\Lambda) D^{(j)}_{s_B s}(p_B,\Lambda)}_{\text{Wigner rotation}} \underbrace{\Lambda^\mu{}_\nu}_{\text{Boost}} \underbrace{\langle p'_B, s'_B|\hat{j}^\nu(0)|p_B, s_B\rangle}_{\text{BF amplitude}}$$

* **Spin Wigner rotation will play a central role for any a moving spinning system.**

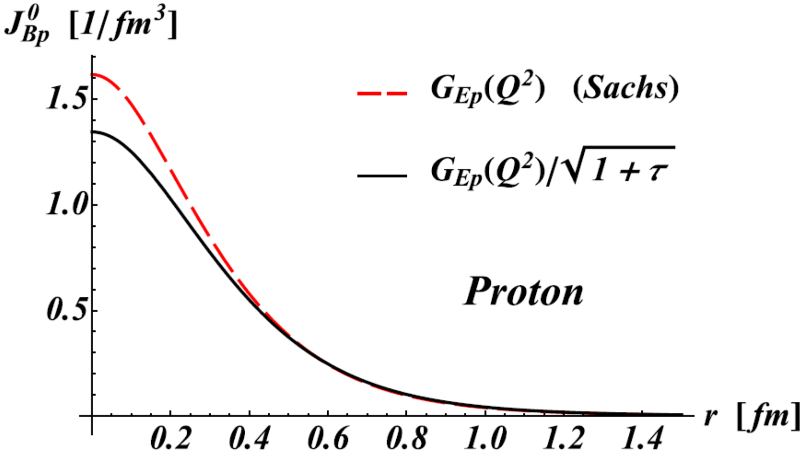
Wigner rotation angle:

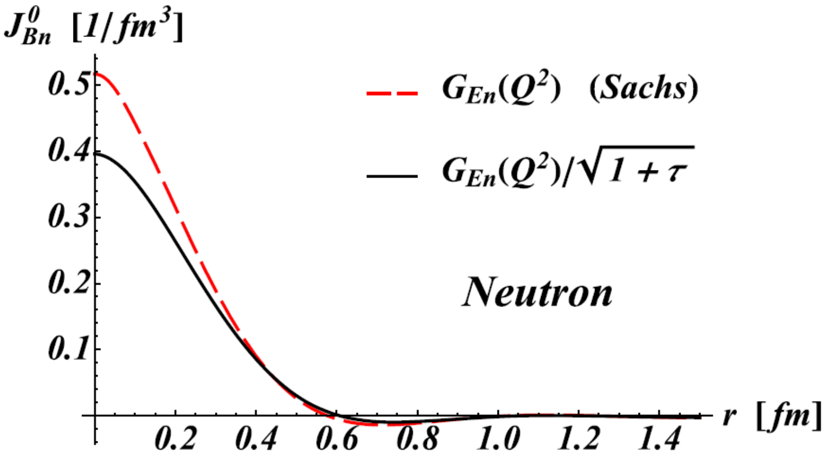
$$\cos\theta = \frac{P^0 + M(1+\tau)}{(P^0+M)\sqrt{1+\tau}}, \quad \sin\theta = -\frac{\sqrt{\tau}P_z}{(P^0+M)\sqrt{1+\tau}}$$

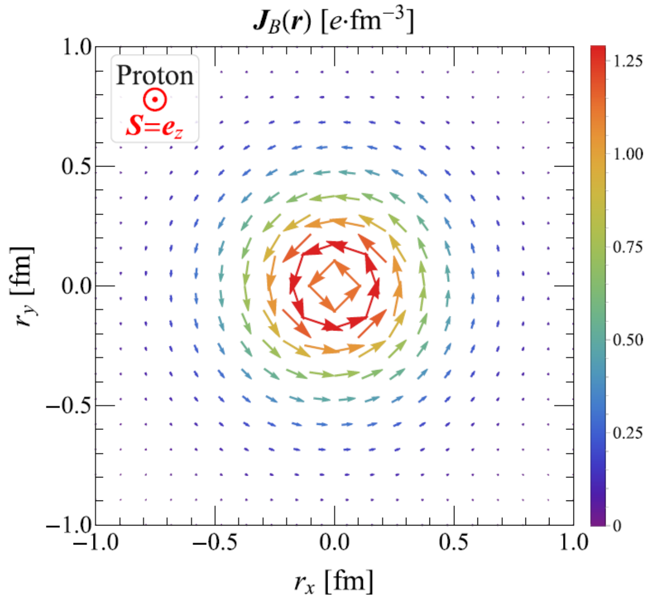
$$p^{(\prime)\mu} = \Lambda^\mu{}_\nu p^{(\prime)\nu}_B$$

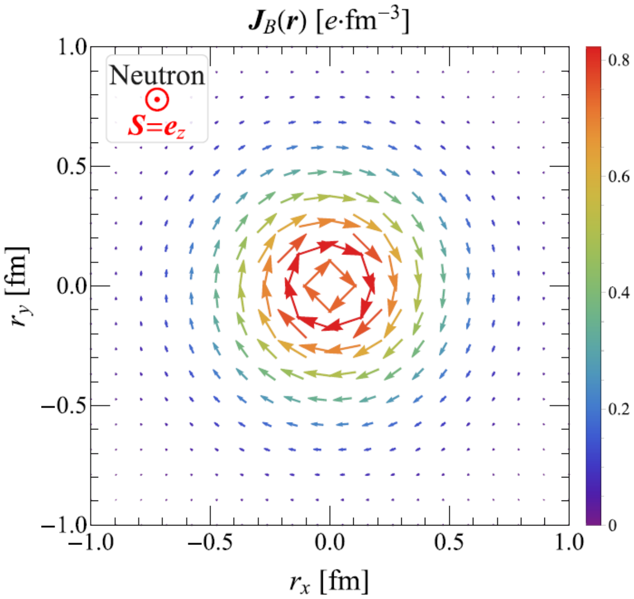
[C. Lorcé, PRL125 (2020) 232002]
[YC, C. Lorcé, PRD106 (2022) 116024]
[YC, C. Lorcé, PRD107 (2023) 096003]

Nucleon relativistic 3D EM four-current distributions









N.B.: Our results are very recently confirmed by A. Freese and G. Miller.

[C. Lorcé, PRL125 (2020) 232002]
[YC, C. Lorcé, PRD106 (2022) 116024]
[A. Freese and G. Miller, PRD 107 (2023) 074036]

Using the tilted LF coordinates

Nucleon relativistic EM four-current distributions

- **EF distributions (2D):**

$$J^0_{\text{EF}}(\boldsymbol{b}_\perp;P_z) = e\int\frac{\mathrm{d}^2\Delta_\perp}{(2\pi)^2}\,e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp}\left[\delta_{s's}\cos\theta+\frac{(\boldsymbol{\sigma}_{s's}\times i\boldsymbol{\Delta})_z}{2M\sqrt{\tau}}\sin\theta\right]\frac{G_E(\boldsymbol{\Delta}^2_\perp)}{\sqrt{1+\tau}}$$

$$+\,e\int\frac{\mathrm{d}^2\Delta_\perp}{(2\pi)^2}\,e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp}\,\frac{P_z}{P^0}\left[-\delta_{s's}\sin\theta+\frac{(\boldsymbol{\sigma}_{s's}\times i\boldsymbol{\Delta})_z}{2M\sqrt{\tau}}\cos\theta\right]\frac{\sqrt{\tau}G_M(\boldsymbol{\Delta}^2_\perp)}{\sqrt{1+\tau}}$$

$$J_{z,\text{EF}}(\boldsymbol{b}_\perp;P_z) = e\int\frac{\mathrm{d}^2\Delta_\perp}{(2\pi)^2}\,e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp}\,\frac{P_z}{P^0}\left[\delta_{s's}\cos\theta+\frac{(\boldsymbol{\sigma}_{s's}\times i\boldsymbol{\Delta})_z}{2M\sqrt{\tau}}\sin\theta\right]\frac{G_E(\boldsymbol{\Delta}^2_\perp)}{\sqrt{1+\tau}}$$

$$+\,e\int\frac{\mathrm{d}^2\Delta_\perp}{(2\pi)^2}\,e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp}\left[-\delta_{s's}\sin\theta+\frac{(\boldsymbol{\sigma}_{s's}\times i\boldsymbol{\Delta})_z}{2M\sqrt{\tau}}\cos\theta\right]\frac{\sqrt{\tau}G_M(\boldsymbol{\Delta}^2_\perp)}{\sqrt{1+\tau}}$$

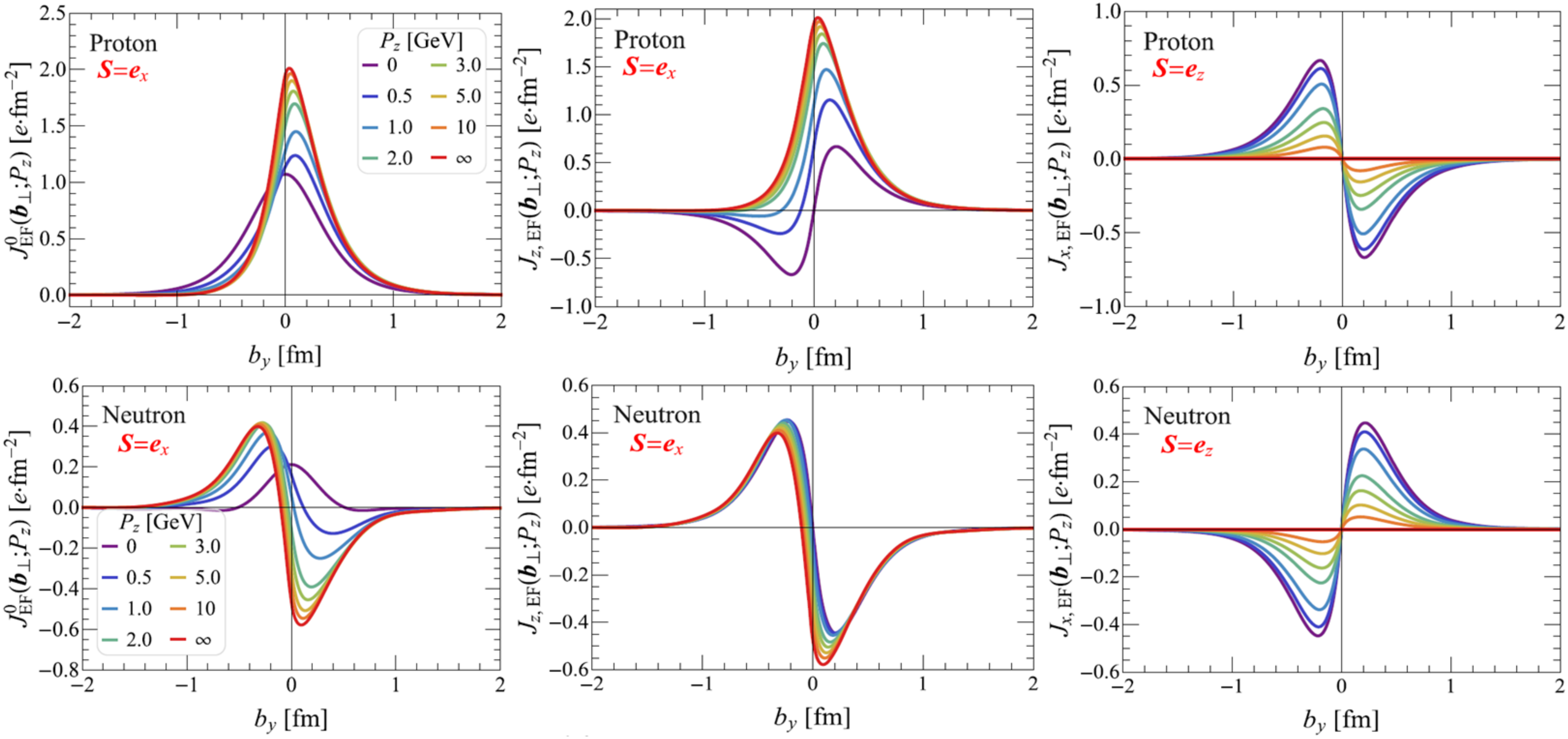
$$\boldsymbol{J}_{\perp,\text{EF}}(\boldsymbol{b}_\perp;P_z) = e(\sigma_z)_{s's}\int\frac{\mathrm{d}^2\Delta_\perp}{(2\pi)^2}\,e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp}\,\frac{(\boldsymbol{e}_z\times i\boldsymbol{\Delta})_\perp}{2P^0}\,G_M(\boldsymbol{\Delta}^2_\perp)$$

free of spin Wigner rotation **suppressed by Lorentz contraction**

➡ **Spin Wigner rotation indeed plays a central role for a moving spinning target.**

[C. Lorcé, PRL125 (2020) 232002]
[YC, C. Lorcé, PRD106 (2022) 116024]
[YC, C. Lorcé, PRD107 (2023) 096003]

Nucleon relativistic 2D EM four-current distributions



Relativistic spatial distributions are in general frame-dependent. The deformations from axial symmetry (J^0) or anti-symmetry ($J^3=J_z$) is mainly due to spin Wigner rotation.

In particular, the 2D LF charge ("+"-component) distribution is reproduced in the IMF:

$$J^+_{\mathrm{LF}}(\boldsymbol{b}_\perp;P^+) = J^0_{\mathrm{EF}}(\boldsymbol{b}_\perp;\infty) = J_{z,\mathrm{EF}}(\boldsymbol{b}_\perp;\infty)$$

Summary & Outlook

1. **Based on the original KMW model (which has inspired us a lot), we generalized the formulation for the estimation of strong EM fields → EKMW model. Our results on the time evolution of magnetic field are confirmed recently by many research works.**

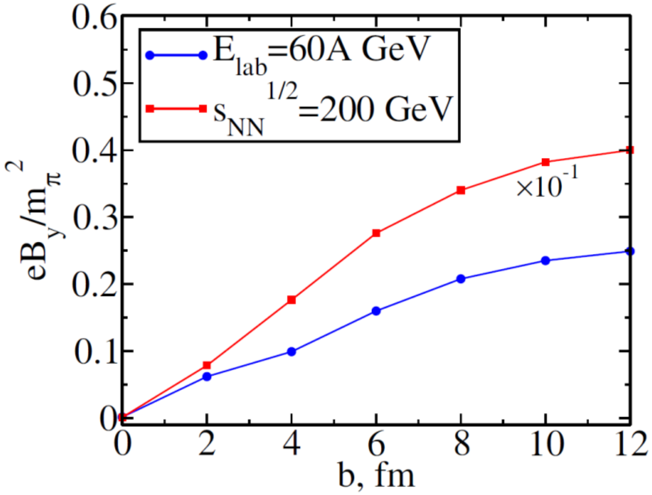
2. **Relativistic distortions of EM four-current distribution arising for any a spinning target with non-vanishing average momenta can be understood as a combination of Lorentz boosts and Wigner spin rotations. The latter are very essential and significant!**

Thank you very much for your attention!

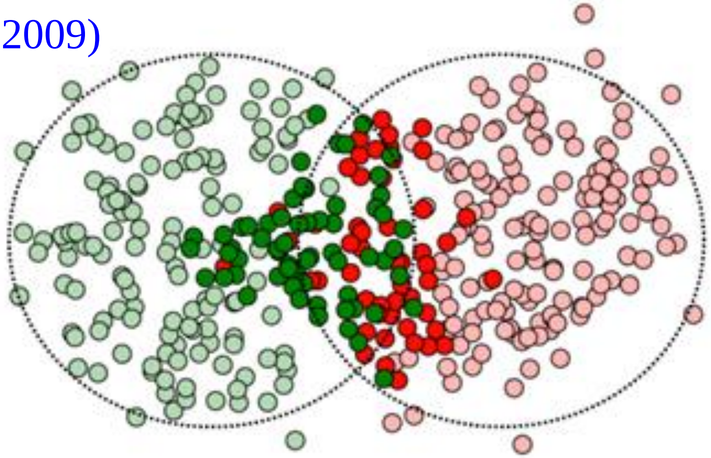
Kharzeev, McLerran & Warringa, NPA 803 (2008) 227-253;
Fukushima, Kharzeev & Warringa, PRD 78, 074033 (2008);
Fukushima, Kharzeev & Warringa, NPA 836, 311 (2010);
Kharzeev, Ann. Phys. 353, 205 (2010);
Kharzeev, Prog. Part. Nucl. Phys. 75, 133 (2014);……

Thanks to D. E. Kharzeev for his brilliant ideas and very illuminating papers!

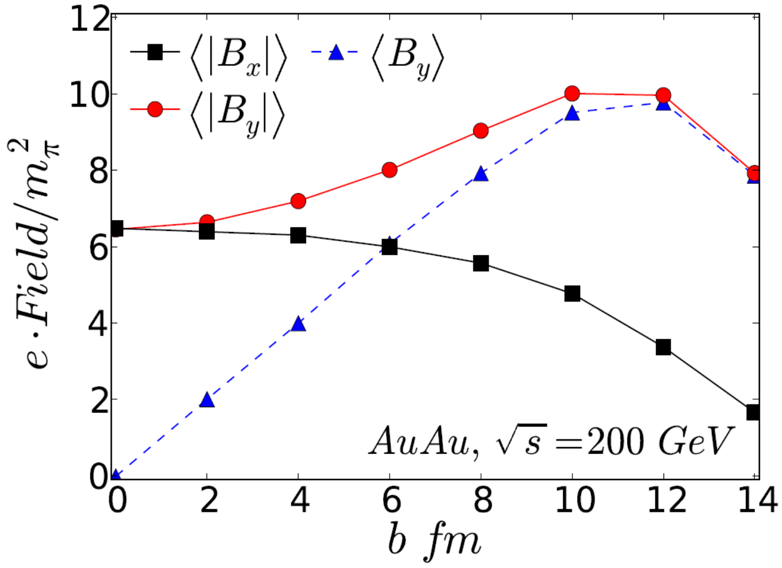
Centrality dependence of the strong magnetic field



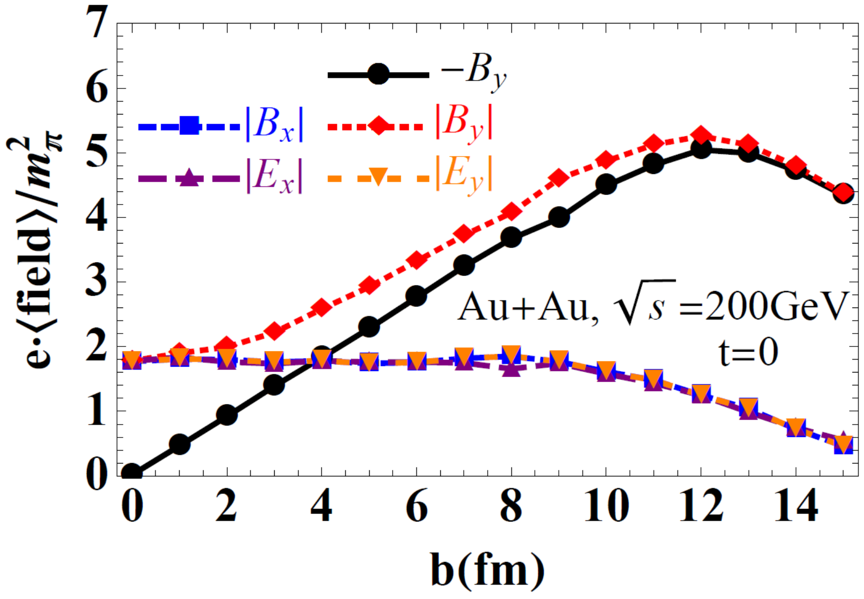
Skokov, Illarionov & Toneev (2009)



Fluctuations of protons’ positions



Bzdak & Skokov (2012)



W.-T. Deng & X.-G. Huang (2012)