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Effects on dilepton radiation induced by a background magnetic field

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Magnetic field in HIC

- Initial $eB \sim (1-10)m_\pi^2$. Decaying.
- Perturbative B treatment relevant in HIC [Guojun Huang, et al, PRD, 2023].
- Explore the EM field effect in hydro stage.

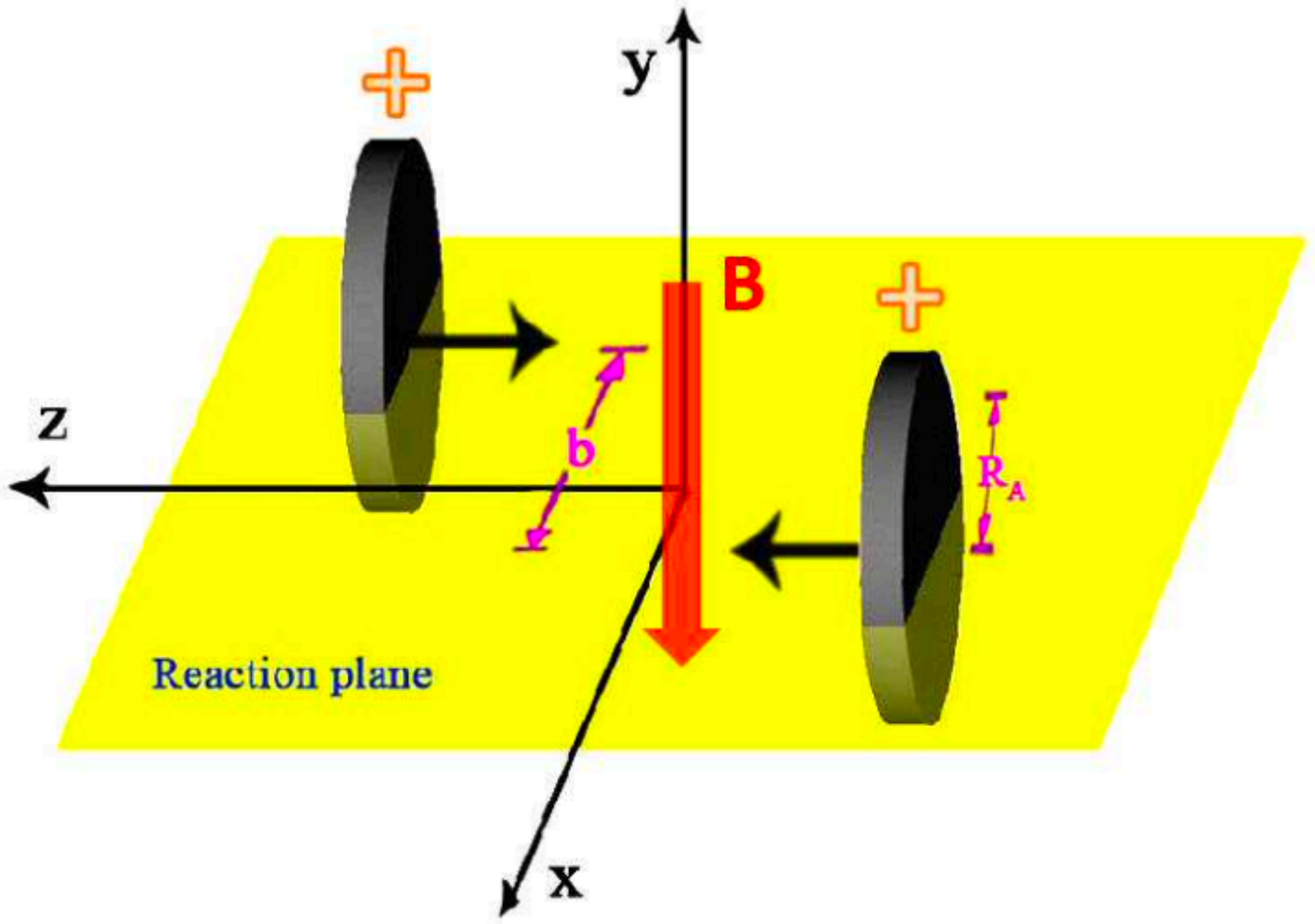
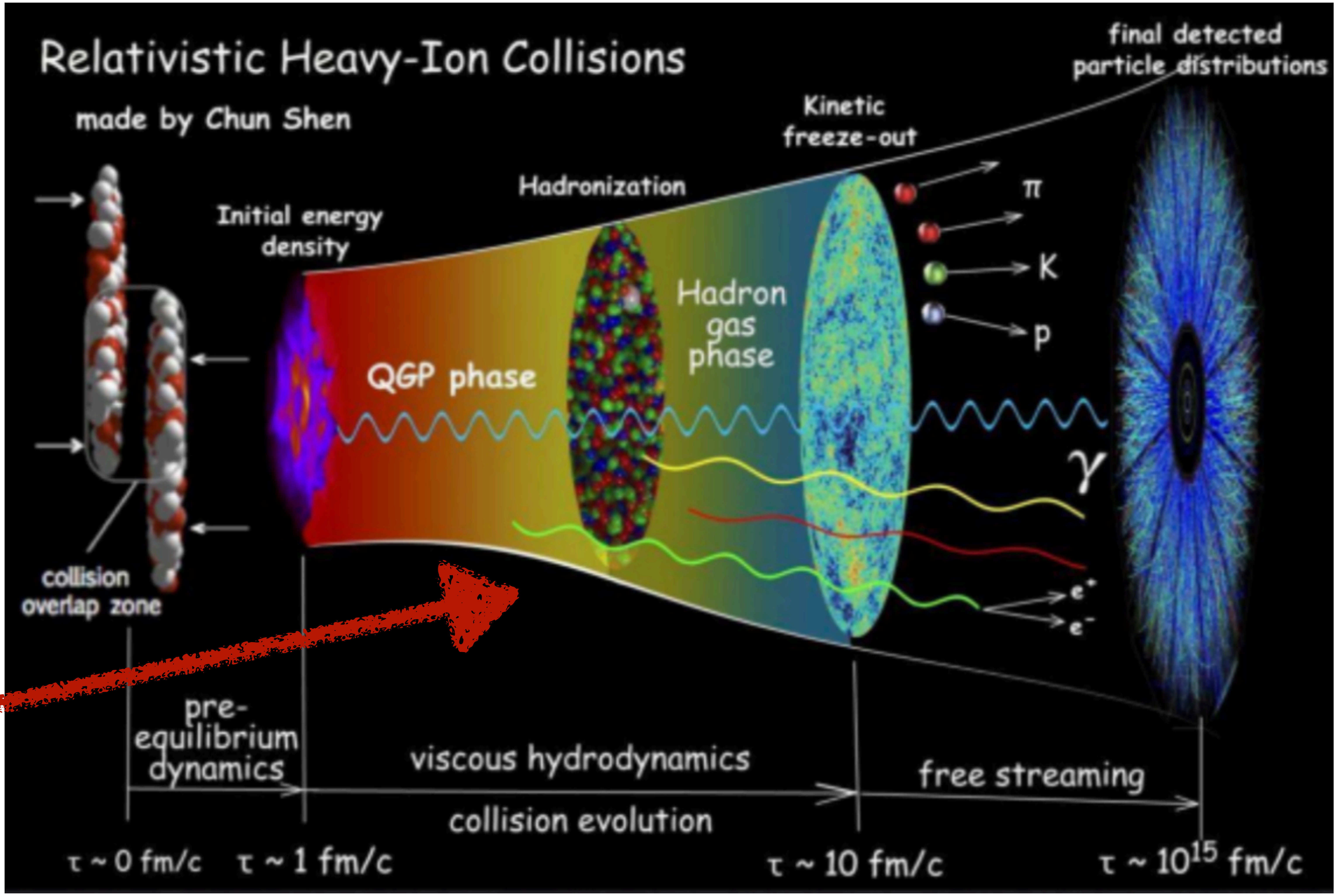


Fig. Cr. Xu-Guang Huang, Rept.Prog.Phys., 2016

Dilepton radiation in HIC

- Hadrons: produced at the freeze-out.
- Dileptons (and real photons): produced throughout the fireball evolution.
- This talk: hydro stage.



Pre-eq dileptons: Xiang-yu Wu's talk after mine

Dilepton radiation: thermometer and magnometer

- Dilepton production rate (DPR): $$\frac{dR}{d^4k} = \frac{\alpha_{em}}{12\pi^4}\frac{n_B(\omega)}{k^2}B(\frac{m_\ell^2}{k^2})\mathrm{Im}\Pi^\mu_\mu(k;T,\mu)$$
- Medium property => Photon self-energy => Dilepton observables.
- Useful and practical thermometer in hydro phase: effective temperature (> freeze-out *T*)
- Expected to be sensitive to external EM field => use dileptons as QGP magnometer? => Direct info on QGP effective magnetic field prior to freeze-out.

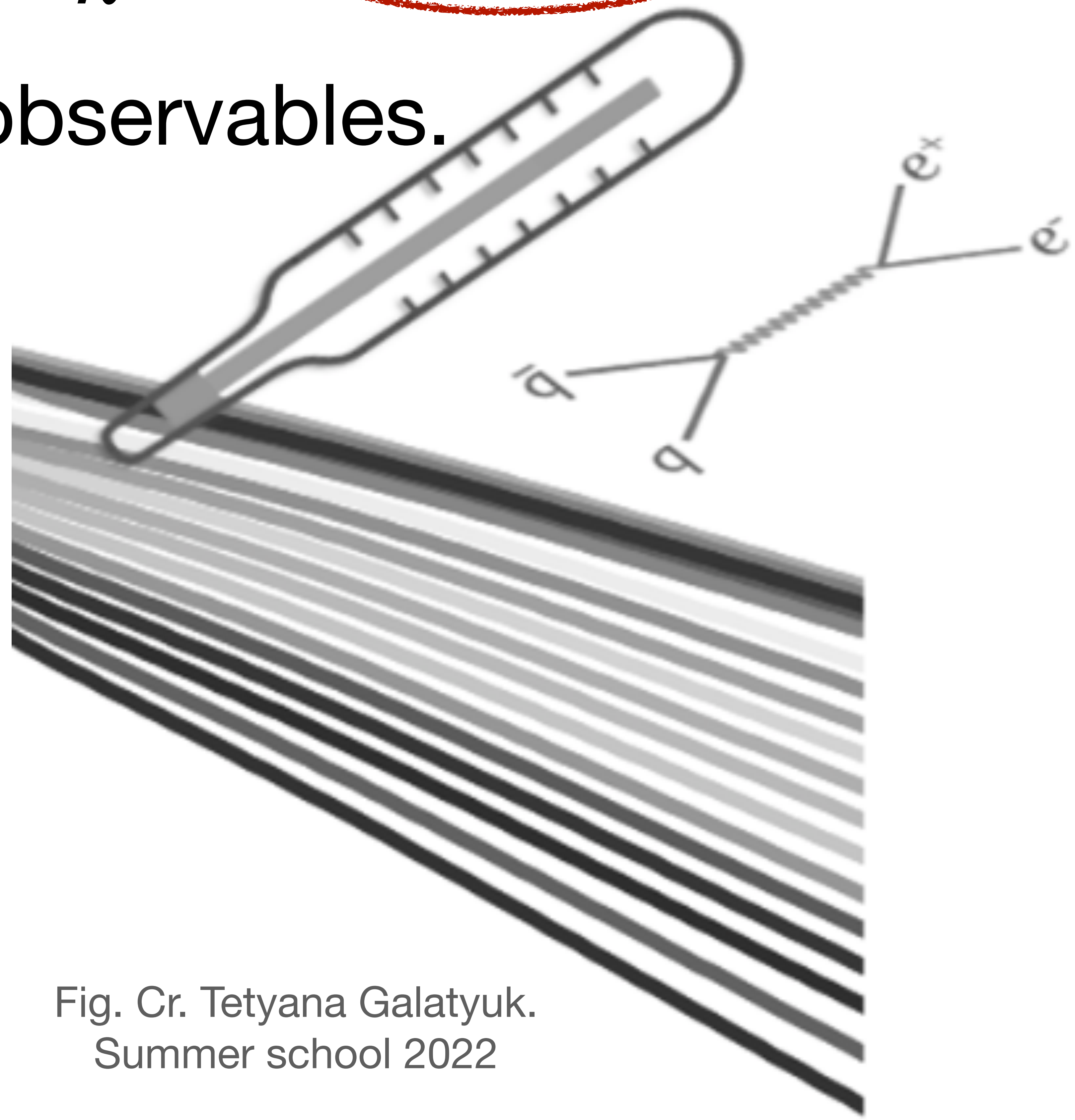


Fig. Cr. Tetyana Galatyuk.
Summer school 2022

$O(B)$ correction

- Π^{μ}_{μ}: scalar => At first sight, lowest correction to dilepton production from small magnetic field is at least $O(B^2)$.
- However a finite fluid velocity $\vec{u}$ induces corrections at $O(B)$ order: an in-fluid electric field $\overrightarrow{E} = -\vec{u} \times \overrightarrow{B}$ by Lorentz transformation => E field drives plasma out-of-equilibrium.
- Solve Boltzmann eq. $\delta f_a = \dfrac{eQ_a \tau_R E^{\mu} p_{\mu}}{T u^{\mu} p_{\mu}} n_F (1 - n_F)$. [J.-A. Sun, L. Yan, 2302.07696]
- Born rate for dilepton production:
$$\frac{dR}{d^4k} = \int \frac{d^3\vec{p}_1 d^3\vec{p}_2}{(2\pi)^6} f(E_1) f(E_2) v_{12} \sigma \delta(k - p_1 - p_2) \, .$$

Other non-eq corrections

- Other non-equilibrium corrections to DPR are systematically considered in a similar manner: Boltzmann eq (+Chapman-Enskog approximation).
- Viscosity [Vujanovic, et al, PRC, 2014]:

$$\delta f_V = n_F(1 - n_F) C_q \frac{p^\alpha p^\beta}{T^2} \frac{\pi_{\alpha\beta}}{\mathcal{E} + \mathcal{P}} .$$

- Diffusion [Denicol, et al, PRC, 2018]:

$$\delta f_D = T n_F(1 - n_F) \left(\frac{n_B}{\mathcal{E} + \mathcal{P}} \mp \frac{1}{3u \cdot p} \right) \frac{p \cdot j_{diff}}{T\hat{\kappa}} .$$

- $f = n_F + \delta f_{EM} + \delta f_V + \delta f_D .$

Finite σ_{el} rate

- Considering only the leading order of α_{EM} => no relaxation => plasma has conductivity $\sigma_{el} = \infty$.

- An effective way to include relaxation: (1) solve Boltzmann eq. w/ $-\frac{\delta f}{\tau_R}$; (2) obtain self-energy by $\Pi^{\mu\nu}(k) = \frac{\delta J^\mu(k)}{\delta A_\nu(k)}$ including τ_R dependence; (3) relate τ_R w/ σ_{el}; (4) now $\mathrm{DPR} \sim \mathrm{Im}\Pi^\mu_\mu$ has a σ_{el} dependence.

Dilepton rate to invariant mass spectrum

- DPR from a single cell w/ temp T, baryon chemical potential μ_B: $\frac{dR}{d^4k}(\omega, \vec{k}; T, \mu_B)$.

- Sum over fluid evolution => Phase-space distribution of all produced dileptons: $\frac{dN}{d^4k} = \int d^4X \frac{dR}{d^4k}(\omega; \vec{k}; T(X), \mu_B(X))$.

- Invariant mass spectrum (for a rapidity window): $\frac{dN}{dM} = M \int_{-y_{min}}^{y_{max}} dy \int d\phi p_T dp_T \frac{dN}{d^4k}$.

- More details: J. Churchill, et al, PRL 2024 & PRC 2024.

$B(\tau)$ and $E(\tau)$ profile

- Decaying B induces (another piece of) E by Faraday law.
- As a function of proper time τ instead of t [Sun, Plumari and Greco, PLB 2021]=> Easier to embed in hydro.

$$B_y(x,y,\tau) = -\rho(x,y)\frac{B_0}{1+\tau/\tau_B}; \quad E_x(t,x,y,\eta_s) = \int_0^{\eta_s} d\chi \frac{\partial B(x,y,\tau=\frac{t}{\cosh\chi})}{\partial\tau}\frac{t}{\cosh\chi}.$$

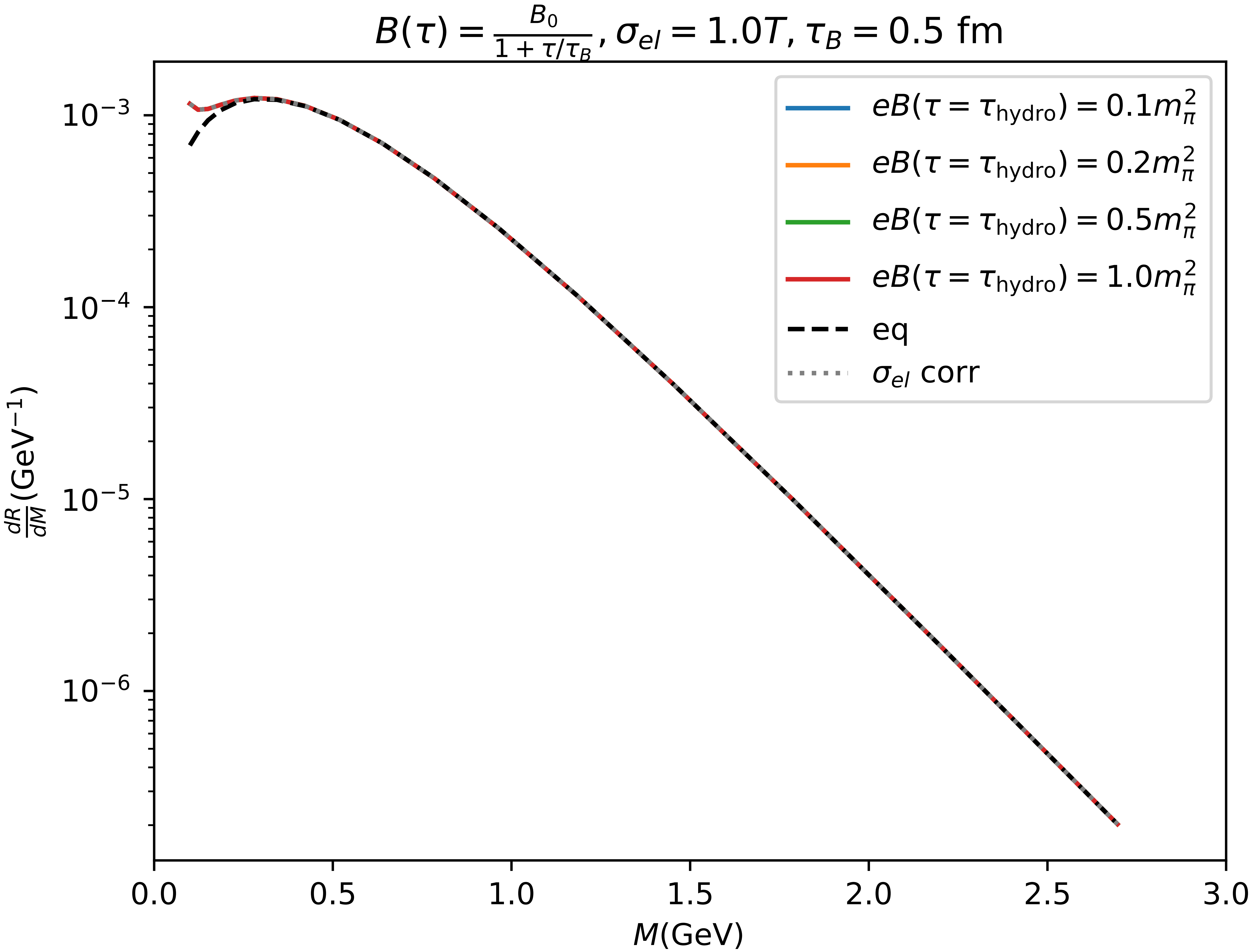
- $\rho(x,y)$: smearing function. Chosen to be Gaussian.
- An addition contribution to $p\cdot E$ in δf_{EM}.

Putting it all together…

- We study the dilepton production for BES energy AuAu@19.6 GeV.
- Multi-stage 3+1D finite-μ_B hydro simulation reproducing hadronic observables.
- Interested in the effective eB in hydro stage => $eB_h \equiv eB(\tau = \tau_{hydro})$, B-field lifetime τ_B as free parameters. $\sigma_{el} = T$ fixed.
- Observables to look at: invariant mass spectrum $\frac{dN}{dM}$, dilepton elliptic flow $v_2^{\ell^+\ell^-}$.

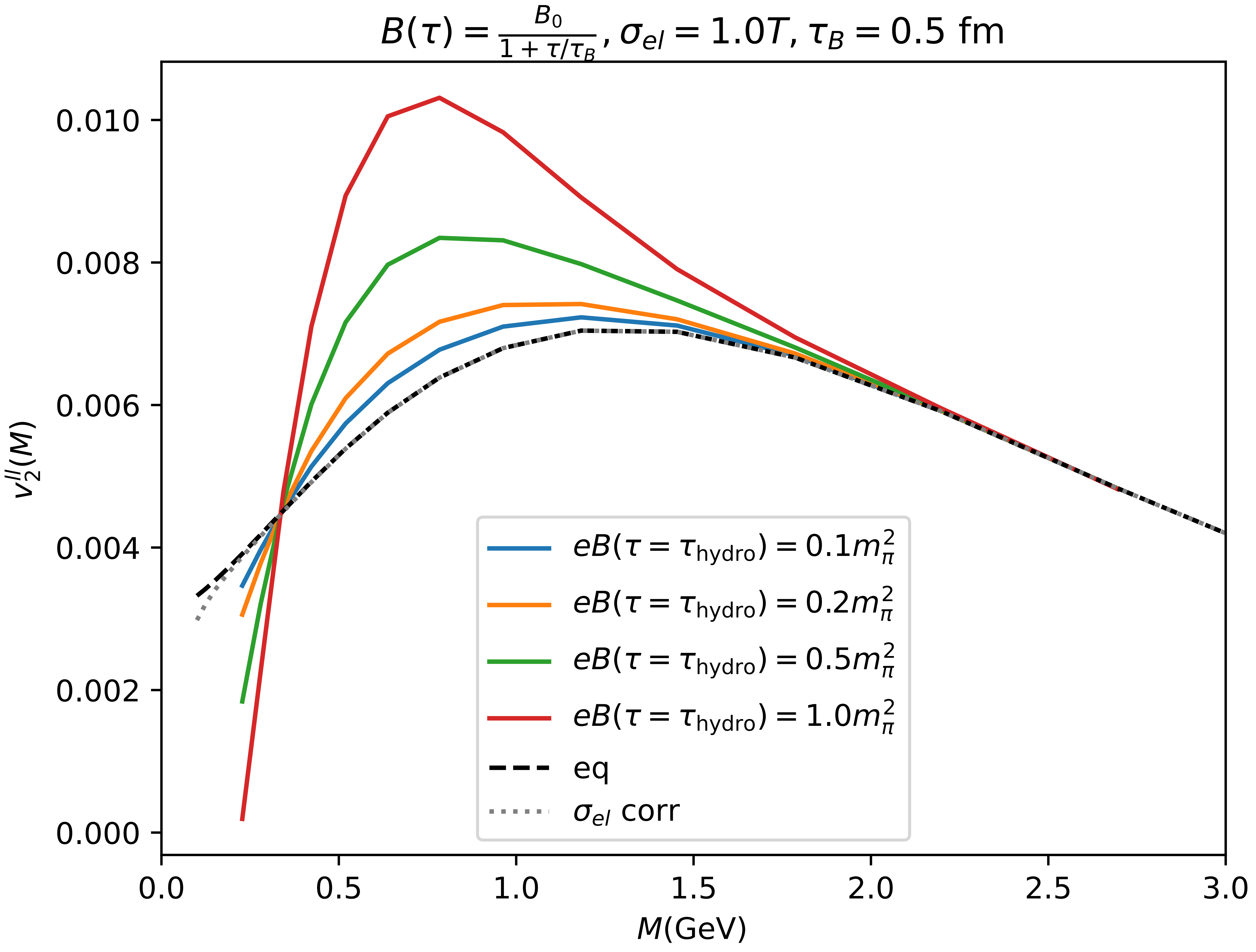
Invariant mass spectrum

- σ_{el} correction gives slightly larger yields at low M => qualitatively similar to NLO rate, but not complete [J. Churchill, et al, PRL 2024]
- No significant correction from EM field.
- Hadronic contribution to low M region not included.



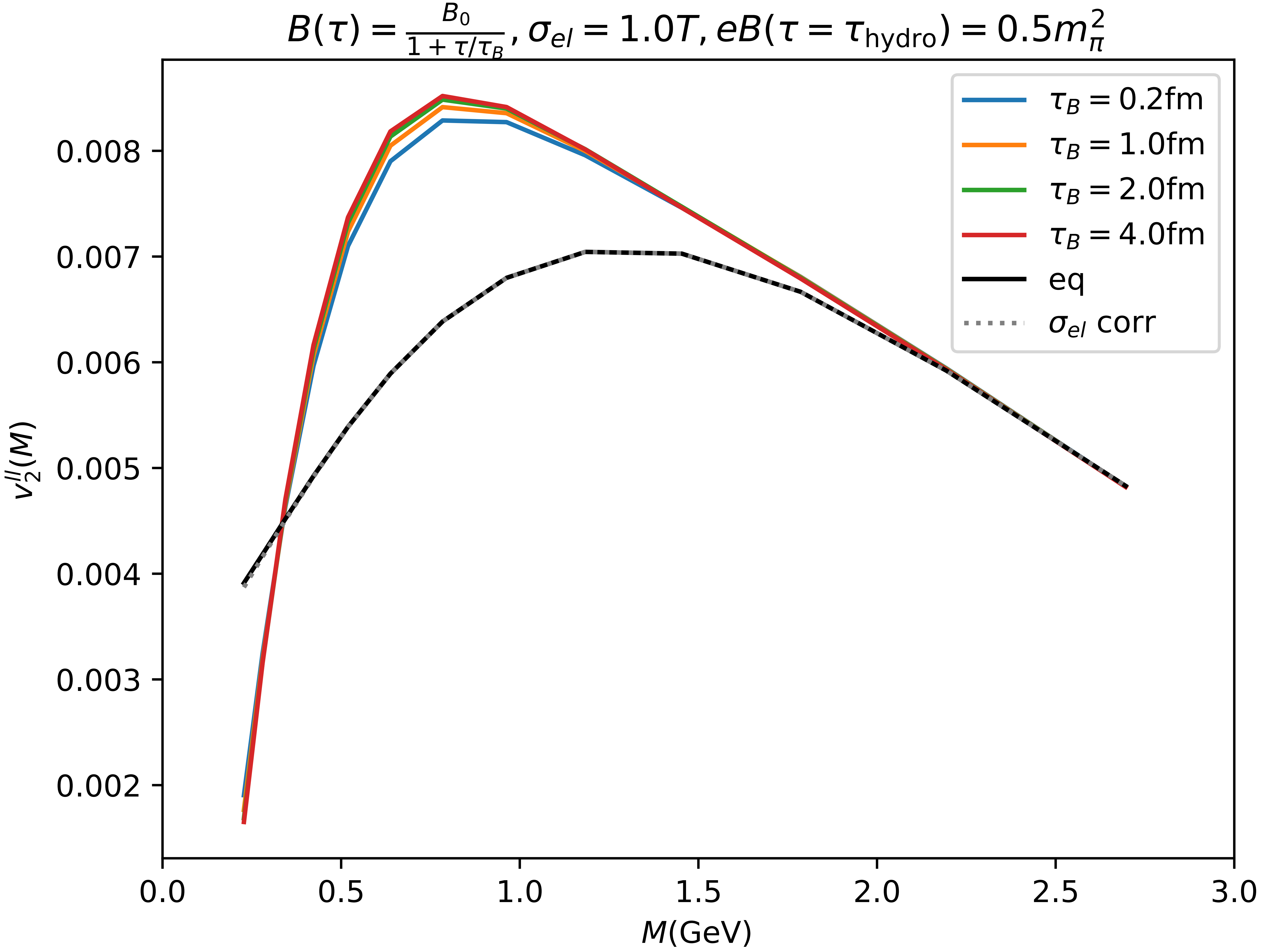
Dilepton $v_2(M)$

- Dilepton v_n defined as $\langle \cos n\phi \rangle + i \langle \sin n\phi \rangle = v_n e^{i\Psi_n}$ => $v_n = \sqrt{\langle \cos n\phi \rangle^2 + \langle \sin n\phi \rangle^2}$
- σ_{el} causes no significant correction.
- Intermediate invariant mass region $v_2(M)$ very sensitive to eB (at hydro starting time).
- A common crossing point at $(M, v_2) \approx (0.4\ \mathrm{GeV}, 0.0045)$.



τ_B dependence

- Only minor *B*-lifetime dependence observed in $v_2(M)$.
  => $v_2(M)$ can be good probe for eB @ the first moment of hydro stage.
- "Feedback" effect:
  Faster decay *B* =>
  Stronger induced *E* =>
  Compensated



Summary

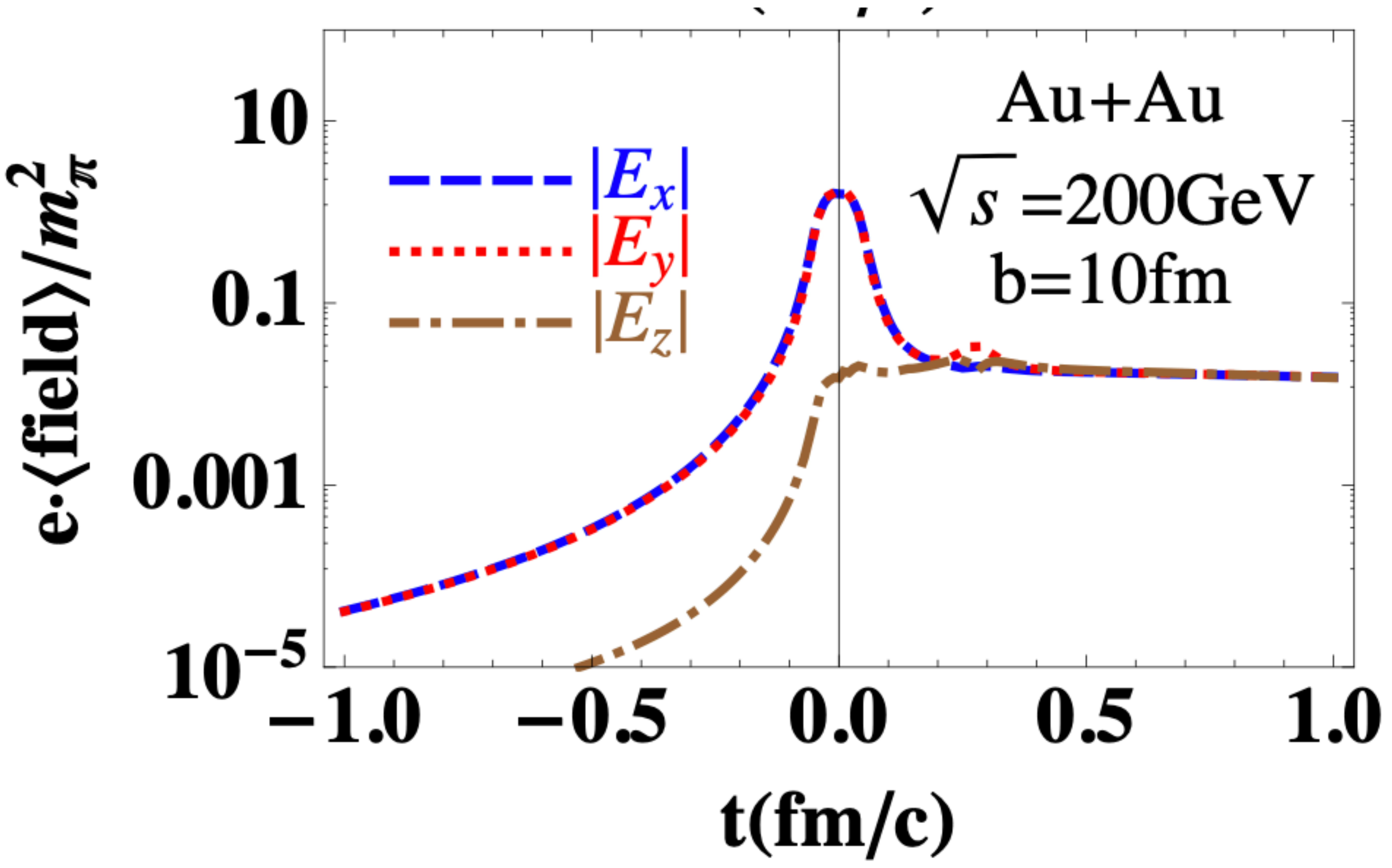
- Possibility of inferring *B* from measured dilepton observables.
- 1st order effect from B and $E \sim \frac{\partial B}{\partial t}$ on dilepton production studied with hydro @ BES energies. Valid for $eB \lesssim T^2$.
- Dilepton $v_2(M)$ at low & medium IMR very sensitive to *B* at hydro stage; not sensitive to the *B* lifetime.
- Perturbative *B* has only moderate effect on dilepton $\frac{dN}{dM}$.

In-fluid EM field

- $E_\mu = F_{\mu\nu} u^\nu$.
- $F_{\mu\nu}$: EM fields in lab frame. Contain $F_{13} = -F_{31} = B_y$ and $F_{01} = -F_{10} = E_x$.

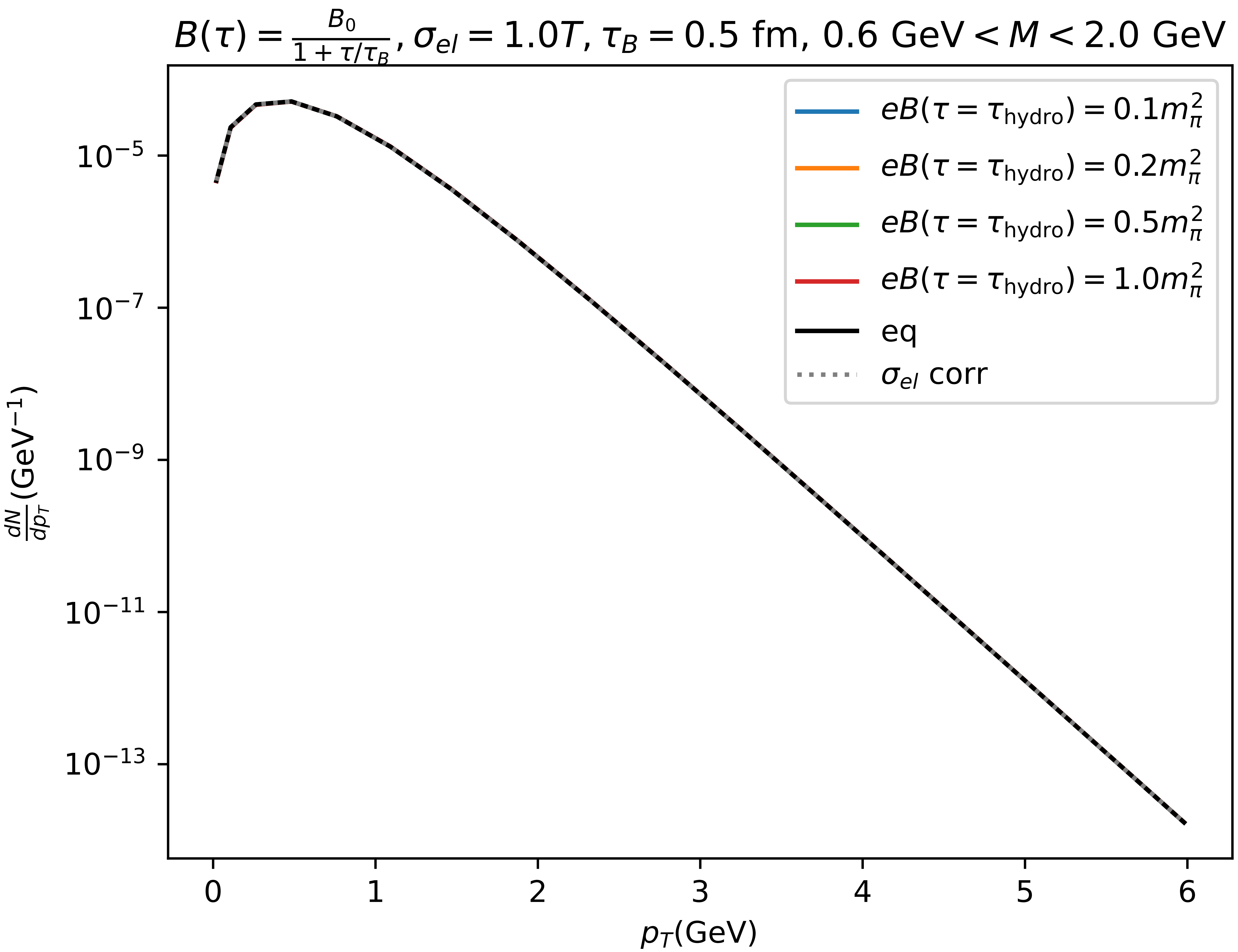
E_z

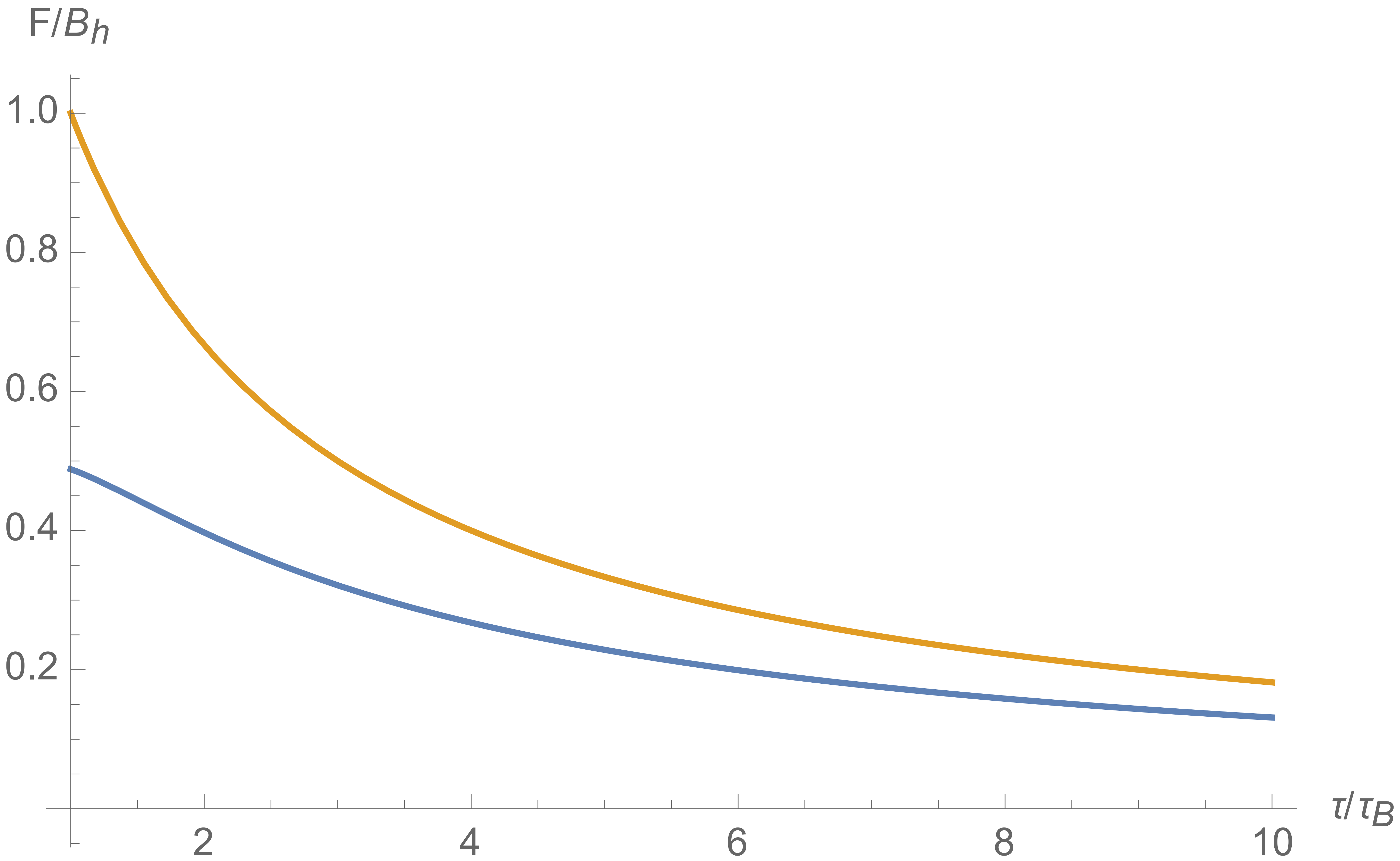
- W.-T. Deng & X.-G. Huang PRC 2012. $E_z \ll E_x$.



p_T spectrum

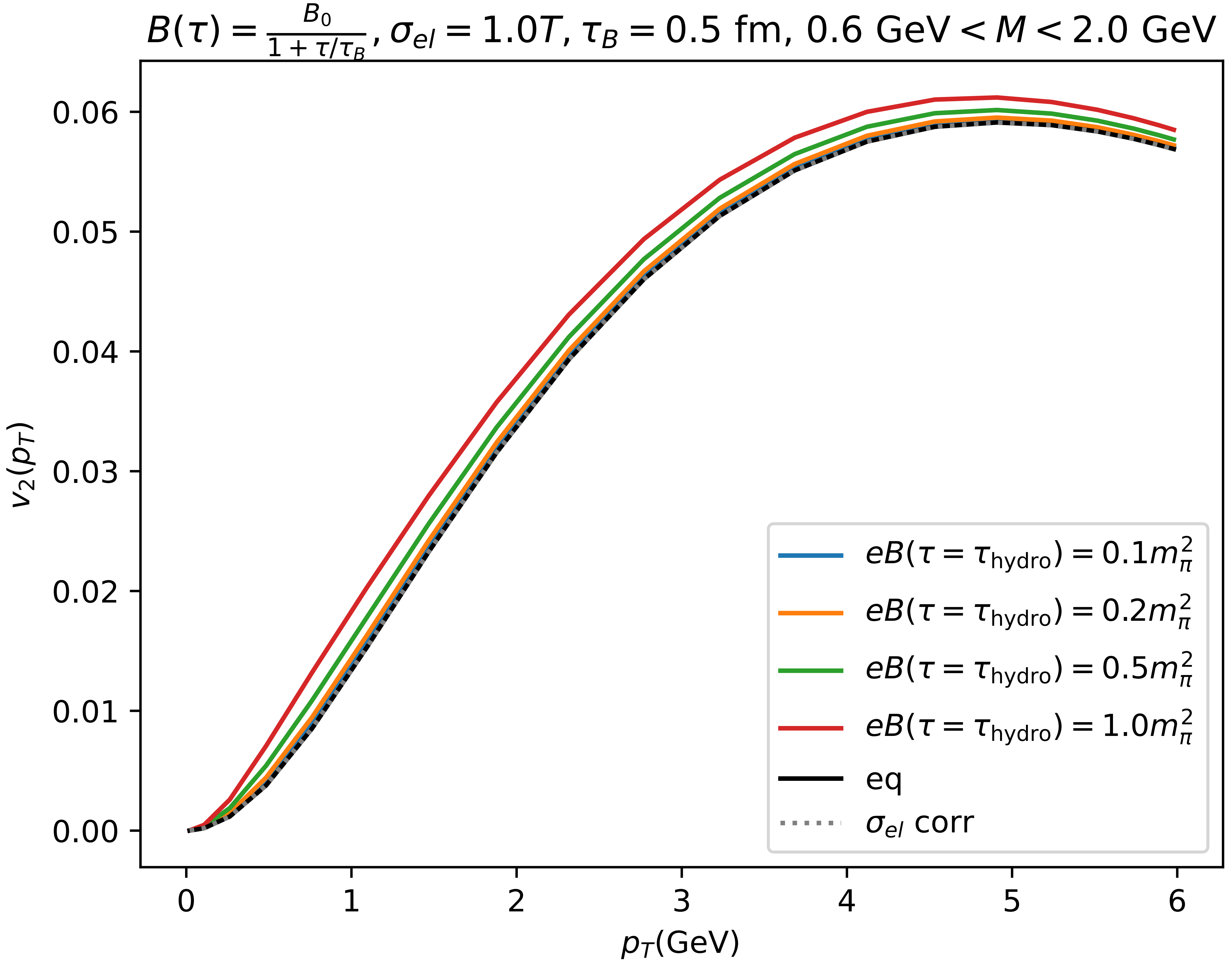
- No significant difference observed in $\frac{dN}{dp_T}$ at medium M window.

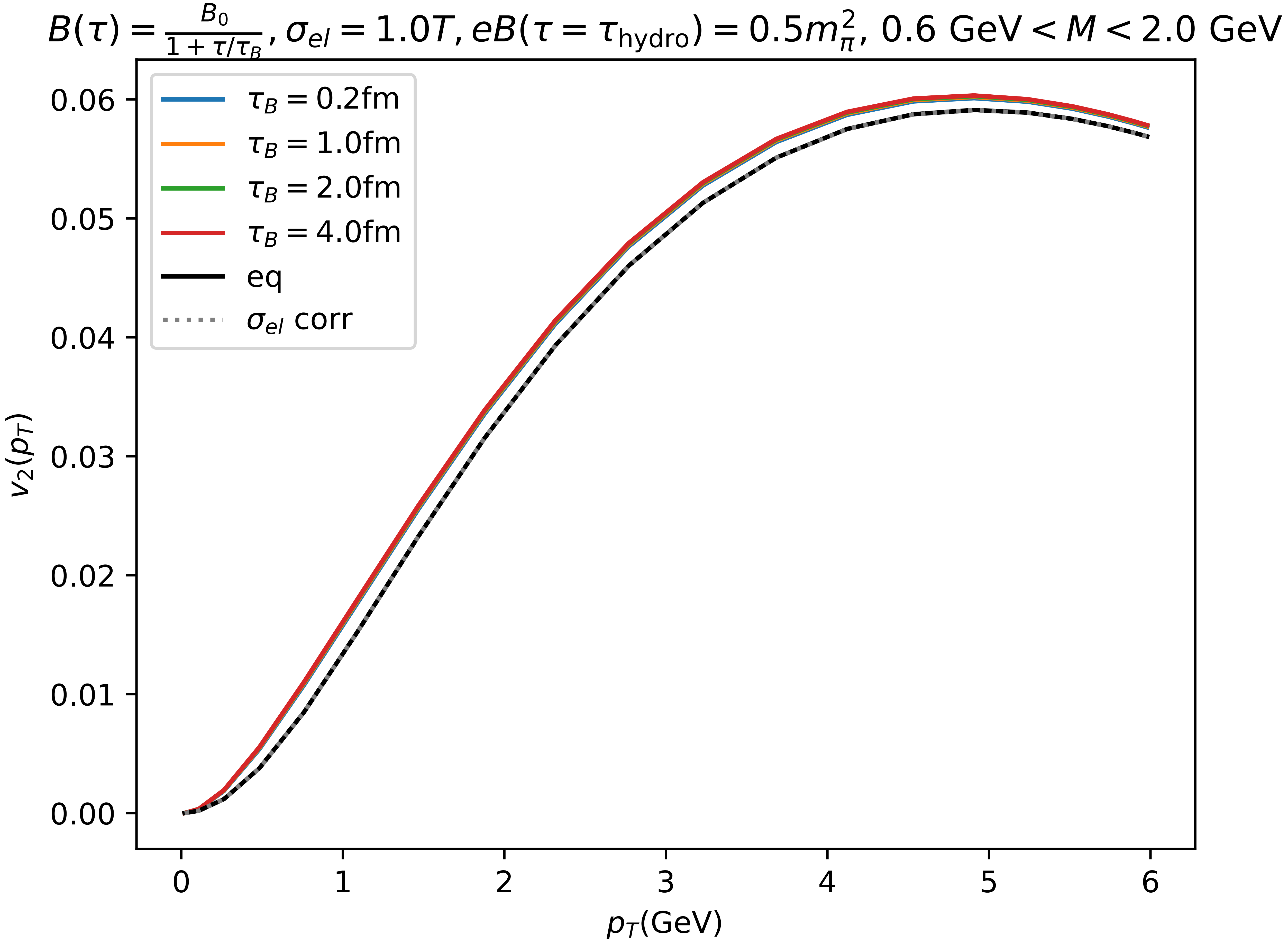




F/B_h
1.0
0.8
0.6
0.4
0.2
2
4
6
8
10
τ/τ_B

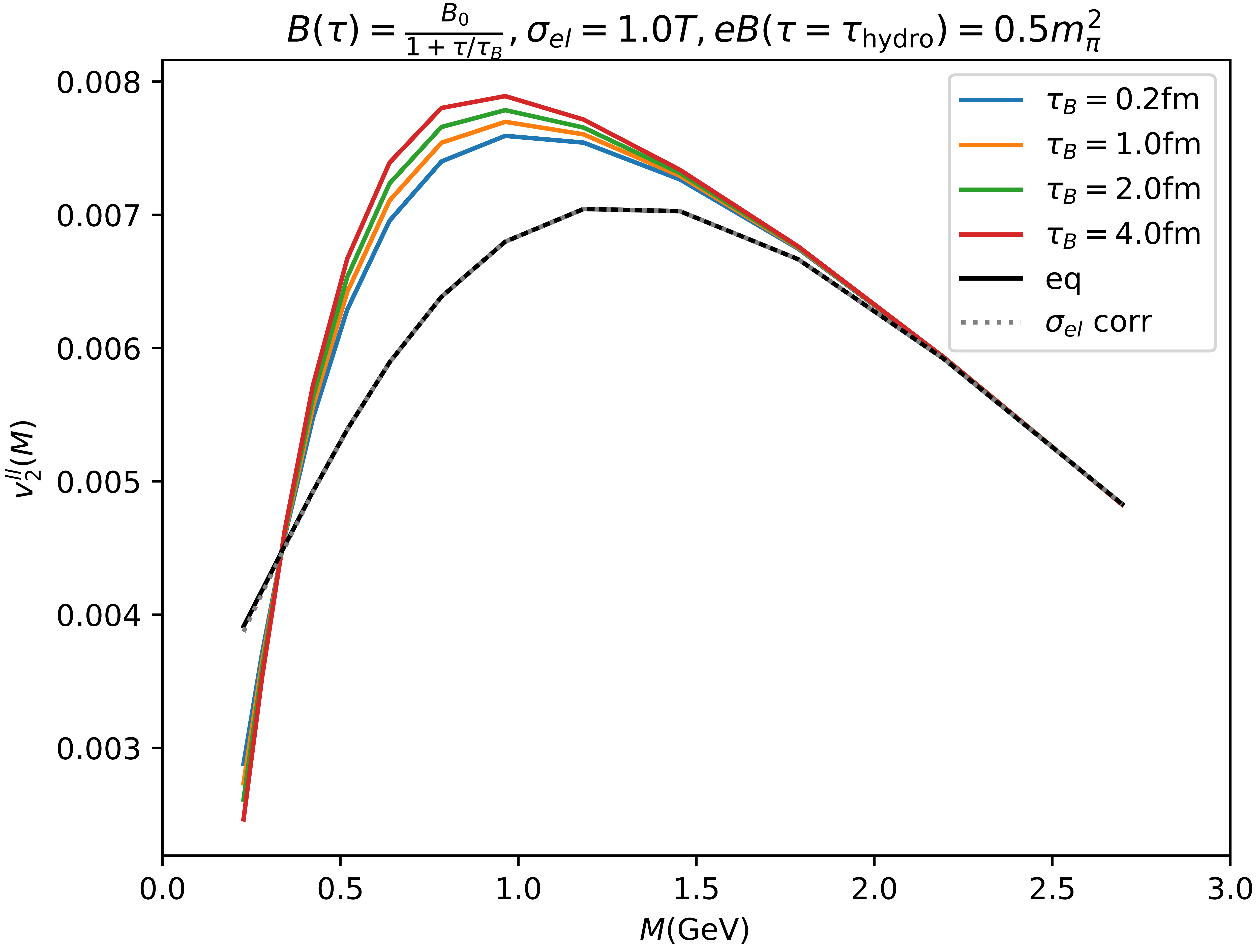
$v_2(p_T)$



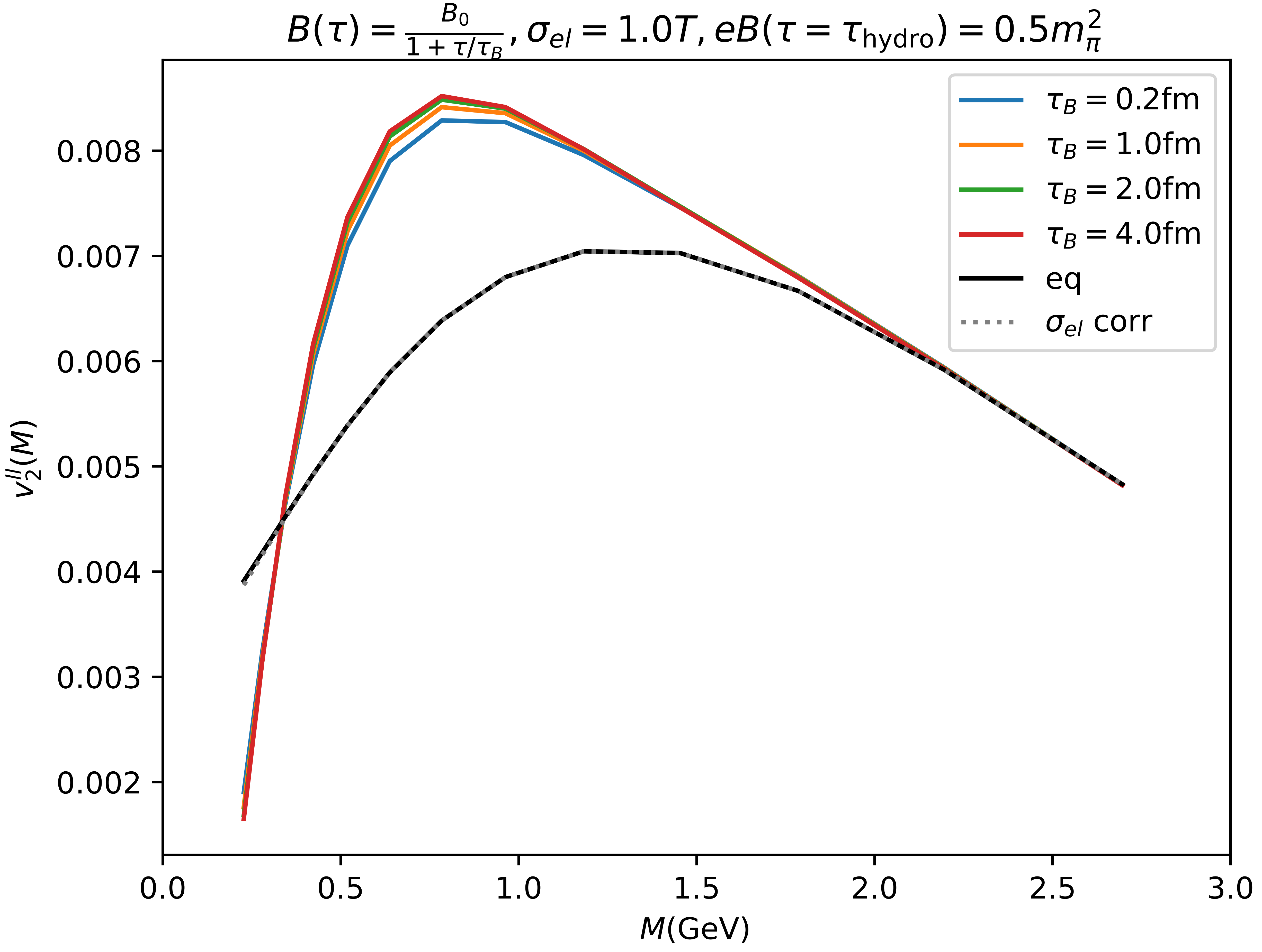


eB correction small.

Only *B* vs *B*+*E*



$B(\tau)=\frac{B_0}{1+\tau/\tau_B}, \sigma_{el}=1.0T, eB(\tau=\tau_{\rm hydro})=0.5m_\pi^2$
$\tau_B=0.2$fm
$\tau_B=1.0$fm
$\tau_B=2.0$fm
$\tau_B=4.0$fm
eq
σ_{el} corr
$v_2^{ll}(M)$
M(GeV)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.003
0.004
0.005
0.006
0.007
0.008



$B(\tau)=\frac{B_0}{1+\tau/\tau_B}, \sigma_{el}=1.0T, eB(\tau=\tau_{\rm hydro})=0.5m_\pi^2$
$\tau_B=0.2$fm
$\tau_B=1.0$fm
$\tau_B=2.0$fm
$\tau_B=4.0$fm
eq
σ_{el} corr
$v_2^{ll}(M)$
M(GeV)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.002
0.003
0.004
0.005
0.006
0.007
0.008