Jet quenching parameter in an expanding QCD plasma

Bin Wu

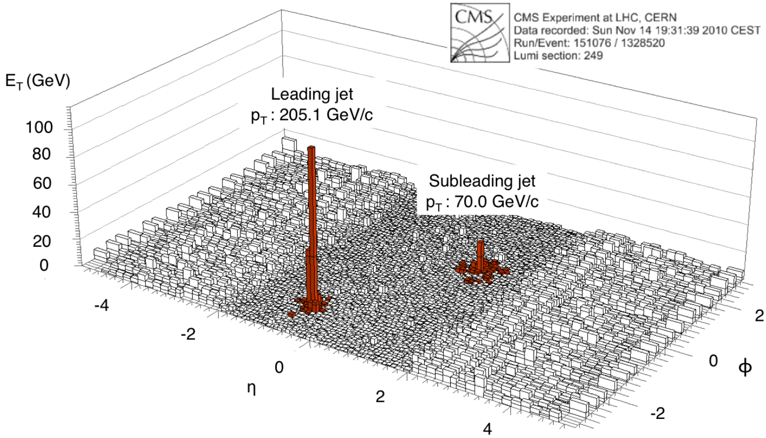
Iancu, Taels and BW, arXiv:1806.07177, to appear in PLB

Hard Probe 2018, Aix-Les-Bains, Savoie, France

Outline

1. **Motivations**
2. **Rethink of $\hat{q}$ in heavy-ion collisions**
3. **Longitudinally boost-invariant $\hat{q}$**
4. **Summary and Perspectives**

1. $\hat{q}$ measured as $p_\perp$-broadening



a dijet in a PbPb collision at $\sqrt{s_{NN}} = 2.76$ **TeV**

CMS: Phys. Rev. C **84**, 024906 (2011) [arXiv:1102.1957]

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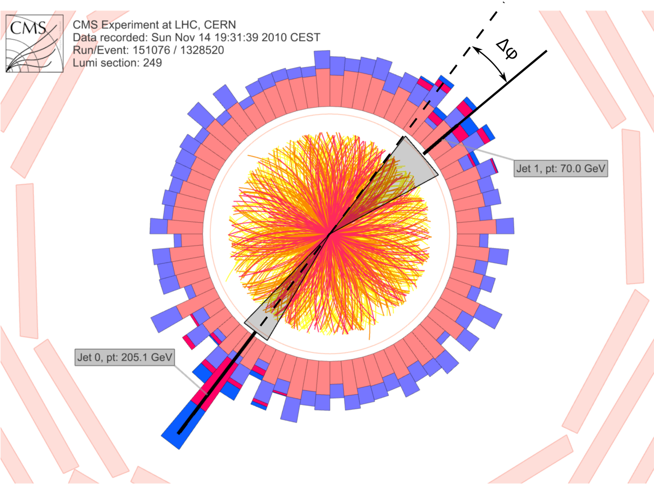

$\hat{q}$ measurement as $\Delta\phi$ correlation

Mueller, BW, Xiao and Yuan, Phys. Lett. B **763**, 208 (2016) [arXiv:1604.04250]

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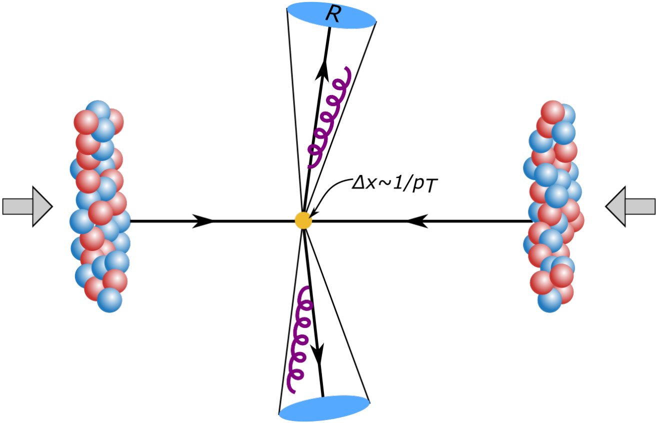

involves both vacuum and medium-induced radiation

Mueller, BW, Xiao and Yuan, Phys. Lett. B **763**, 208 (2016) [arXiv:1604.04250]

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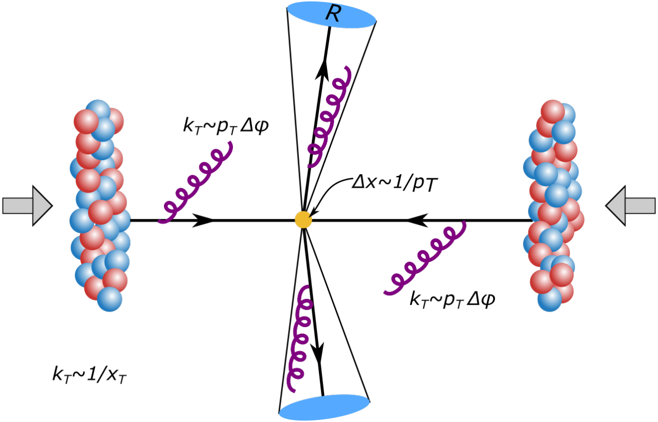

Vacuum: $-\frac{\alpha_s(C_F+C_F)}{\pi}\ln^2(p_T x_T)$

Sun, Yuan and Yuan, Phys. Rev. Lett. 113, no. 23, 232001 (2014)

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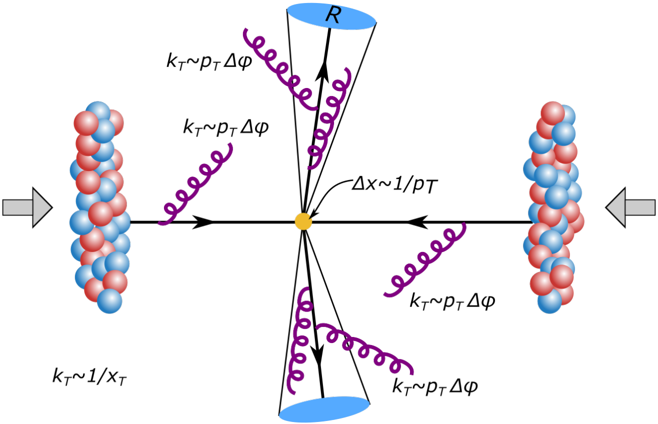

Vacuum: $-\frac{\alpha_s(C_F+C_F)}{\pi}\ln^2(p_T x_T) - \frac{\alpha_s(C_F+C_F)}{\pi}\ln(p_T x_T)\ln(R^2)$

Sun, Yuan and Yuan, Phys. Rev. Lett. 113, no. 23, 232001 (2014)

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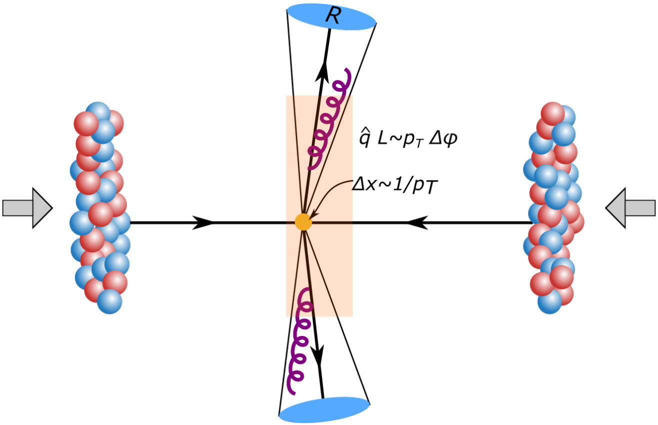

Static medium (Brick): $-2\frac{1}{4}x_\perp^2\hat{q}\left[1+\frac{\alpha_s N_c}{2\pi}\ln^2(L/l_0)\right]$

Liou, Mueller, BW (2013); Blaizot, Mehtar-Tani (2014); Iancu (2014)

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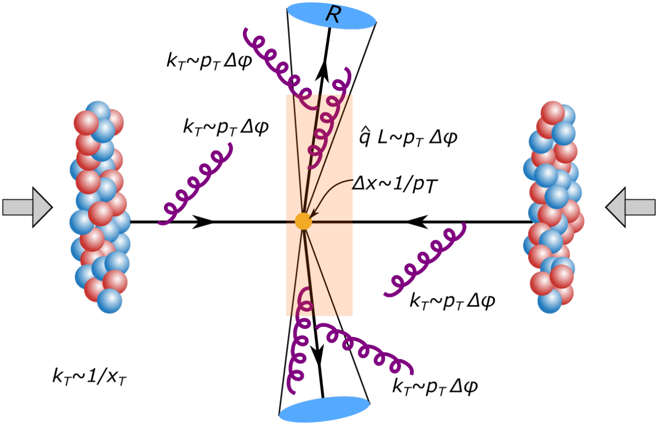
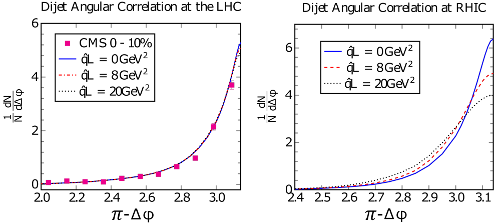


Factorization of vacuum & medium double logs

illustrated in DIS off big nuclei in

Mueller, BW, Xiao and Yuan, Phys. Rev. D **95**, 034007 (2017) [arXiv:1608.07339]

1. $\hat{q}$ measured as $p_\perp$-broadening



Mueller, BW, Xiao and Yuan, Phys. Lett. B 763, 208 (2016)
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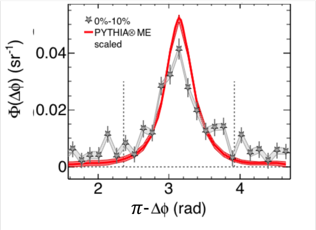


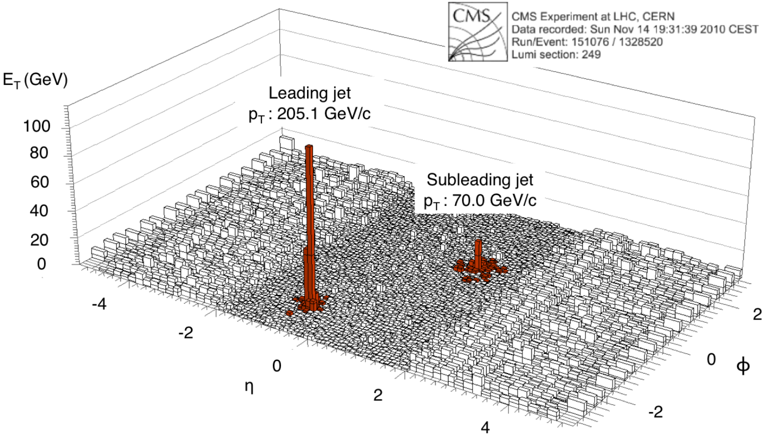
STAR: Phys. Rev. C 96, 024905 (2017)
[arXiv:1702.01108]

$\hat{q}$ is encoded in the broadening of jets in ϕ (and η)

Shu-Yi Wei's talk

For some more elaborated discussions: Chen, Qin, Wei, Xiao and Zhang (2017); Stasto, Wei, Xiao, Yuan (2018); Luo, Cao, He and Wang (2018); Gyulassy, Levai, Liao, Shi, Yuan, Wang (2018); Tannenbaum (2018) $\cdots$

2.1 From Brick to reality: mission complicated



Jet: collimated spray of "particles" in η-ϕ space

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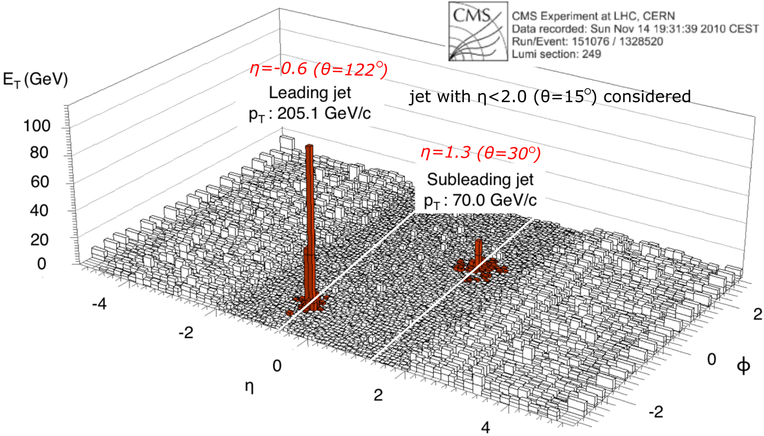

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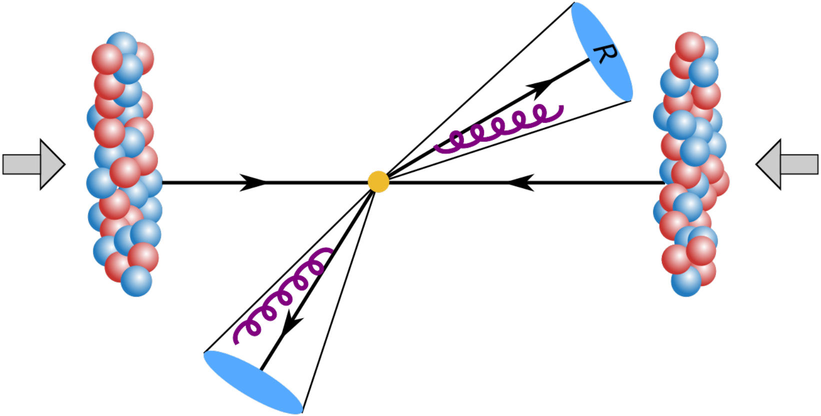

The same event seen in space

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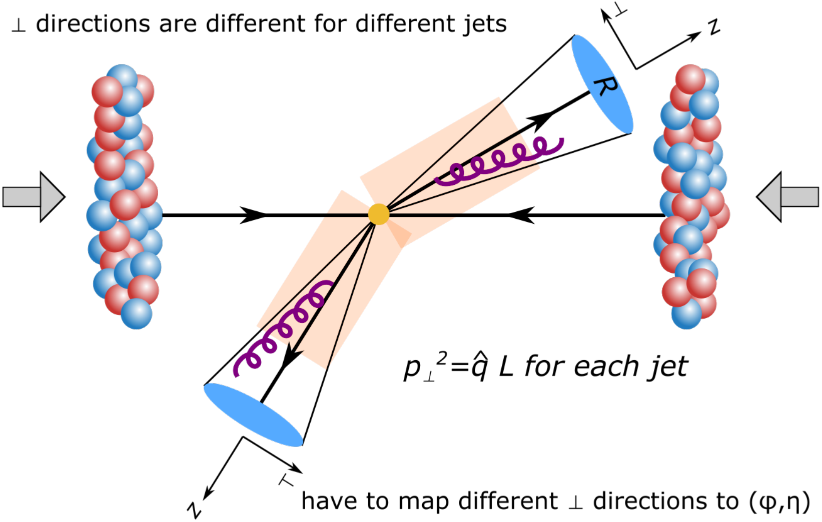

Complication: different $\perp$ direcctions (and $\hat{q}$) to (ϕ, η)

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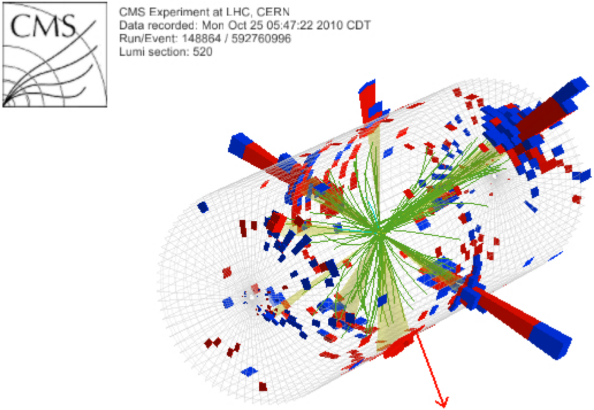
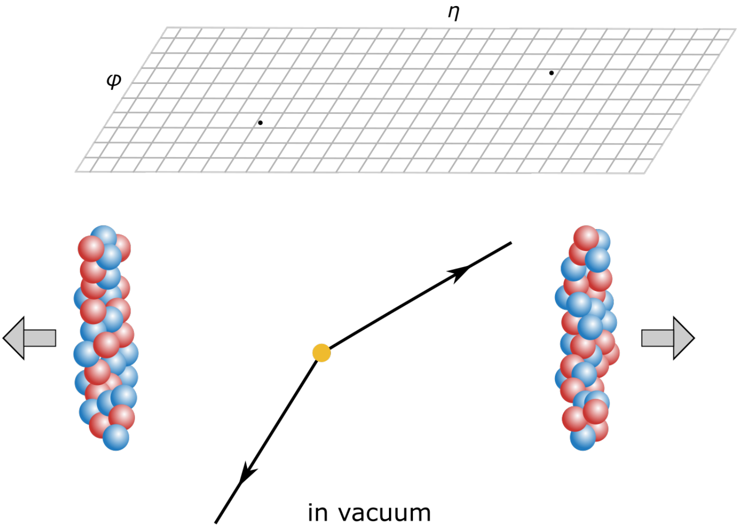


9 jet event in pp

Things may get more complicated!

2.2 A shortcut: choose new coordinates



Focus on final-state interaction based on factorization

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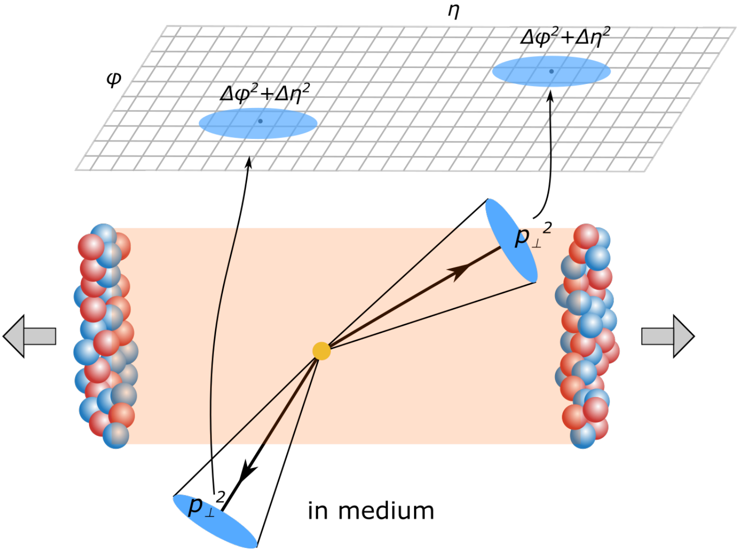

Calculate $\Delta\phi$ and $\Delta\eta$ of each jet

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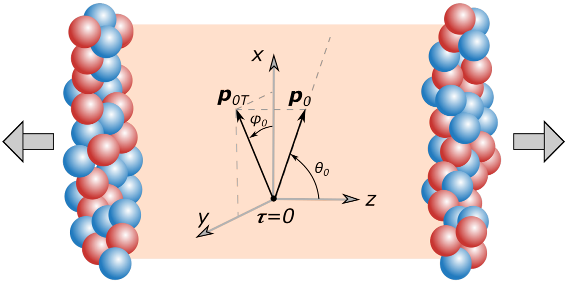

Consider one parton producet at $\tau \approx 0$

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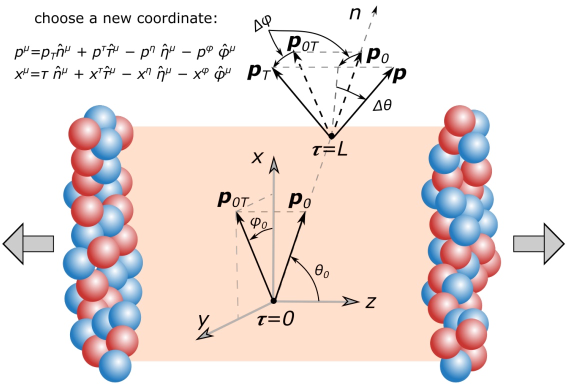
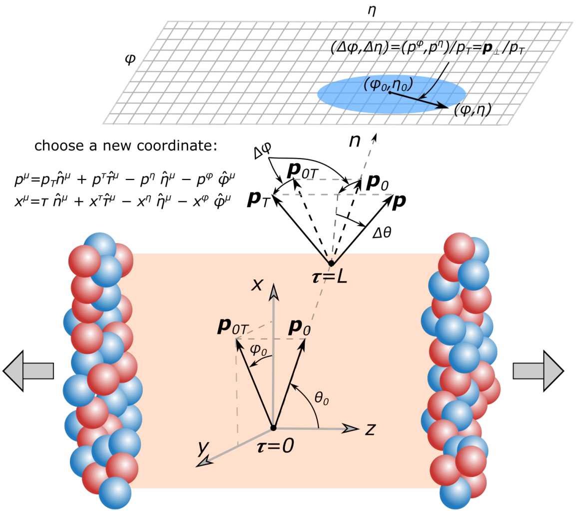


$p_0^\mu \to p^\mu$ at $\tau = L$, decoupled from bulk matter

2.2 A shortcut: choose new coordinates



In new coordinates, $\mathbf{p}_\perp = p_T(\Delta\phi, \Delta\eta)$.

2.3 A byproduct: redefinition of $\hat{q}$

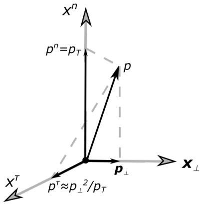
1. **QFT in new coordinates:** $p \cdot x \approx p^n x^\tau + p^\tau x^n - \mathbf{p}_\perp \cdot \mathbf{x}_\perp$

$$\hat{n}^\mu = \frac{p_0^\mu}{p_T} = (\cosh\eta_0, \cos\phi_0, \sin\phi_0, \sinh\eta_0), \qquad \hat{\tau}^\mu = (\cosh\eta_0, 0, 0, \sinh\eta_0),$$

$$\hat{\phi}^\mu \equiv (0, \sin\phi_0, -\cos\phi_0, 0), \qquad \hat{\eta}^\mu \equiv (-\sinh\eta_0, 0, 0, -\cosh\eta_0).$$

2. **Correspond to Brick model**

	$(x^n, x^\tau, x^\eta, x^\phi)$	(t, x, y, z)
Energy loss	$p^n = p_T$	$p^0 = E$
Time	$x^\tau = \tau = \sqrt{t^2 - z^2}$	$x^0 = t$
Transverse	$\mathbf{p}_\perp = (p^\eta, p^\phi) = p_T(\Delta\eta, \Delta\phi)$	(p^x, p^y)



3. $\hat{q}$ **in new coordinates**

$$\hat{\mathbf{q}} = \frac{\mathbf{d}}{\mathbf{d}\tau}\langle \mathbf{p}_\perp^2 \rangle = \mathbf{p}_T^2 \frac{\mathbf{d}}{\mathbf{d}\tau}\langle \boldsymbol{\Delta}\phi^2 + \boldsymbol{\Delta}\eta^2 \rangle.$$

4. **Generality**

Just like LC/Milne coordinates, all formalisms (BDMPSZ, GLV, high-twist) can be adapted into this new frame.

3.1 Longitudinal boost-invariance

In a Longitudinally boost-invariant plasma:

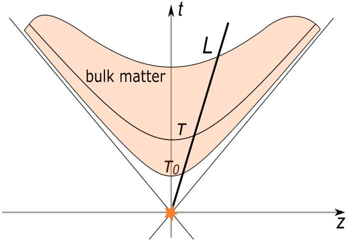
$$\frac{\mathrm{d}N}{\mathrm{d}^2\boldsymbol{p}_\perp} \simeq \frac{1}{\pi\mathcal{Q}_0^2(L)}\,\mathrm{e}^{-\frac{\boldsymbol{p}_\perp^2}{\mathcal{Q}_0^2(L)}} \quad \Leftrightarrow \quad \frac{\mathrm{d}N}{d\Delta\phi d\Delta\eta} \simeq \frac{p_T^2}{\pi\mathcal{Q}_0^2(L)}\,\mathrm{e}^{-\frac{p_T^2(\Delta\phi^2+\Delta\eta^2)}{\mathcal{Q}_0^2(L)}}$$

where $\hat{q}$ **depends only** τ **and** $\Delta\phi$ **and** $\Delta\eta$ **are also longitudinally boost-invariant, that is,**

$$\mathcal{Q}_0^2(L) \equiv \int_{\tau_0}^{L} d\tau\,\hat{q}_0(\tau)$$

$$\hat{q}_0(\tau) \simeq \hat{q}_0(\tau_0)\left(\frac{T(\tau)}{T_0}\right)^3 \simeq \hat{q}_0(\tau_0)\left(\frac{\tau_0}{\tau}\right)^\beta .$$

Here, $\frac{\mathrm{d}N}{\mathrm{d}^2\boldsymbol{p}_\perp} = \int \frac{\mathrm{d}^2\boldsymbol{r}_\perp}{(2\pi)^2}\,\mathrm{e}^{-\mathrm{i}\boldsymbol{p}_\perp\cdot\boldsymbol{r}_\perp}\,S(\boldsymbol{r}_\perp).$



For an expanding plasma, see also: Baier, Dokshitzer, Mueller and Schiff, Phys. Rev. C **58**, 1706 (1998) [hep-ph/9803473]; Zakharov, hep-ph/9807396; Arnold, Phys. Rev. D **79**, 065025 (2009) [arXiv:0808.2767]; BW and Ma, Nucl. Phys. A **848**, 230 (2010) [arXiv:1003.1692].

3.2 Radiative correction to $\hat{q}$

At next leading order:

$$\delta S(\boldsymbol{r}) \simeq -\frac{\alpha_s N_c r^2}{4} \text{ Re } \int \frac{\mathrm{d}\omega}{\omega^3} \int_{\tau_0}^{L} \mathrm{d}\tau_2 \int_{\tau_0}^{\tau_2} \mathrm{d}\tau_1$$

$$\times \left(\nabla_{\boldsymbol{B}_2} \cdot \nabla_{\boldsymbol{B}_1}\right)^2 \left[G(\boldsymbol{B}_2, \tau_2; \boldsymbol{B}_1, \tau_1) - G_0(\boldsymbol{B}_2, \tau_2; \boldsymbol{B}_1, \tau_1)\right]\Big|_{\boldsymbol{B}_1=\boldsymbol{B}_2=0},$$

where $\omega = k_T$, and

$$G(\boldsymbol{B}_2, \tau_2; \boldsymbol{B}_1, \tau_1) \equiv \frac{i\omega}{2\pi D(\tau_2, \tau_1)} \mathrm{e}^{\frac{-i\omega}{2D(\tau_2,\tau_1)}[c_1 \boldsymbol{B}_1^2 + c_2 \boldsymbol{B}_2^2 - 2\boldsymbol{B}_2 \cdot \boldsymbol{B}_1]},$$

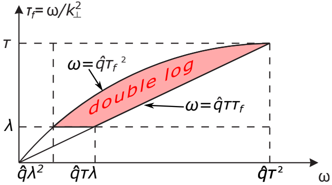
with $c_1 \equiv c(\tau_2, \tau_1)$, $c_2 \equiv c(\tau_1, \tau_2)$ and the following definitions for the functions $D(\tau_2, \tau_1)$ and $c(\tau_2, \tau_1)$:

$$D(\tau_2, \tau_1) = \pi\nu\sqrt{\tau_1\tau_2}\left[J_\nu\left(2\nu\Omega_1\tau_1\right) Y_\nu\left(2\nu\Omega_2\tau_2\right) - J_\nu\left(2\nu\Omega_2\tau_2\right) Y_\nu\left(2\nu\Omega_1\tau_1\right)\right],$$

$$c(\tau_2, \tau_1) = \frac{\pi\nu\sqrt{\tau_1\tau_2}\Omega_2}{\sin(\pi\nu)}\left[J_{\nu-1}\left(2\nu\Omega_2\tau_2\right) J_{-\nu}\left(2\nu\Omega_1\tau_1\right) + J_{1-\nu}\left(2\nu\Omega_2\tau_2\right) J_\nu\left(2\nu\Omega_1\tau_1\right)\right].$$

3.2 Radiative correction $\hat{q}$

Resummation of medium double logs:



$$\hat{q}(\tau) = \hat{q}_0(\tau)\,\frac{\mathrm{I}_1\left(2\sqrt{\bar{\alpha}}\,Y\right)}{\sqrt{\bar{\alpha}}\,Y} \approx \hat{q}_0(\tau)\left\{1 + \frac{\bar{\alpha}}{2}\ln^2\frac{\tau}{\lambda(\tau)}\right\}$$

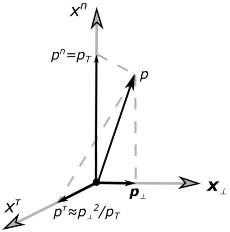
where $Y = \ln(\tau/\lambda(\tau))$ and $\lambda = 1/T(\tau)$ is the thermal wavelength.

In contrast with Brick, it is quasi-local.

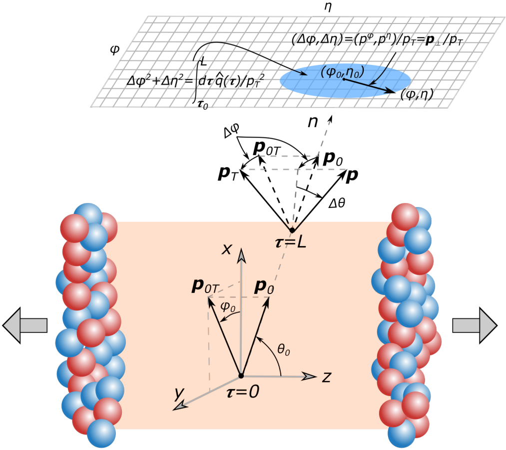
Summary & Perspectives

Summary: $\hat{q}$ can be defined as broadening in ϕ-η

New coordinates:
a bridge between Brick and experiments



e.g.



Perspectives: pQCD (EFT) calculation of $\gamma/Z/W$-jet correlation (with Chien & Shao)