Photon production using the higher-twist formalism

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University of Regina

[Based on PRC **112**, 025204 (2025)]

C3NT Jet-soft Correlation Workshop

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University of Regina

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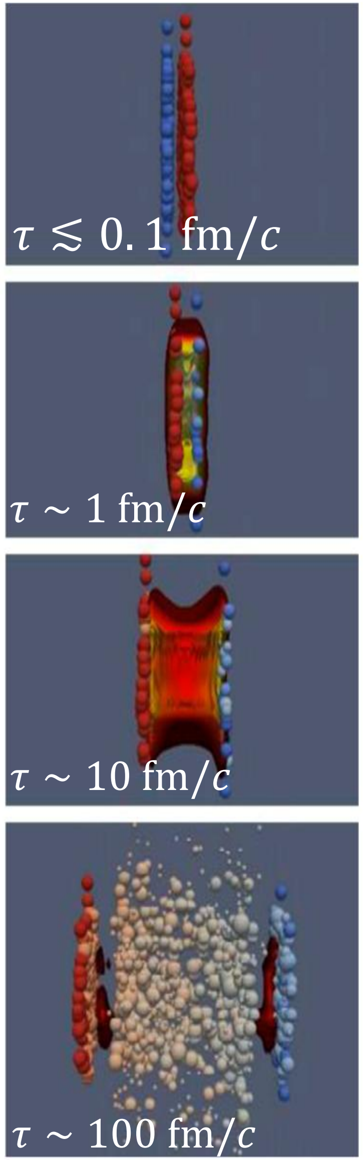
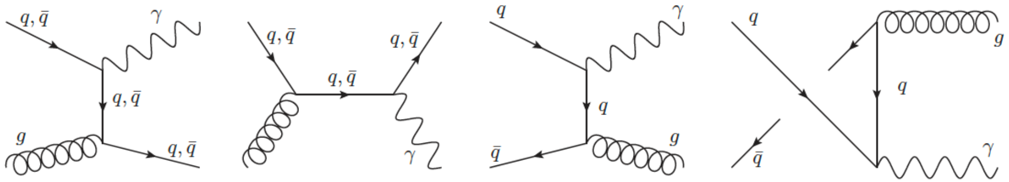
Sources of EM probes from Jets

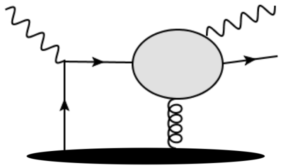
Figure ref. J. Bernhard, H. Elfner (Petersen), MADAI Collaboration



- **Onset of collisions:**
  - Primordial photons:



  - Jet-Glasma photons:



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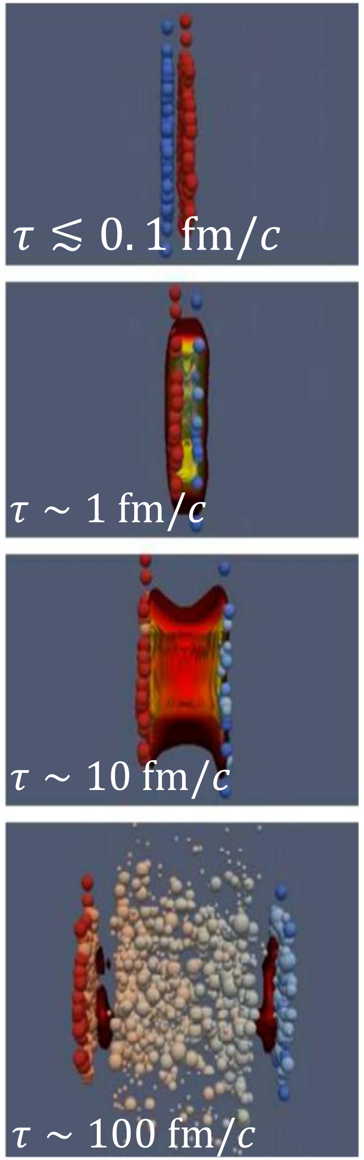

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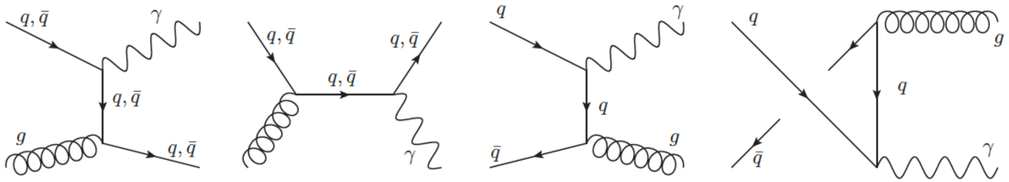

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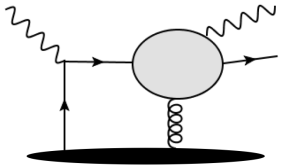
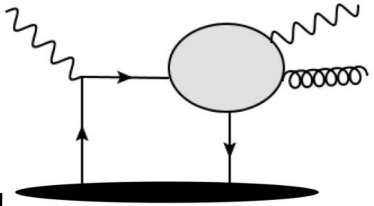


- Pre-hydrodynamical evolution/jet-medium interaction
  - Glasma → QGP: An increase in quark occupations induces ⇒
  - EM probes ***directly*** sensitive to ***dynamics*** of quark occupation!



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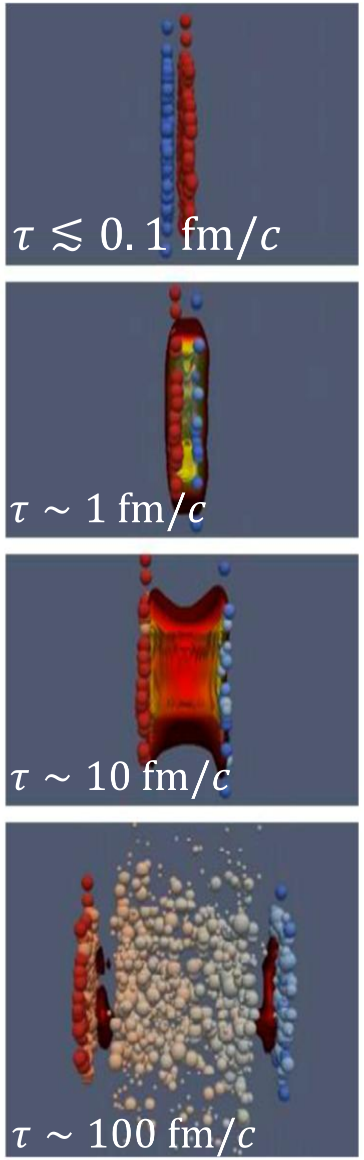

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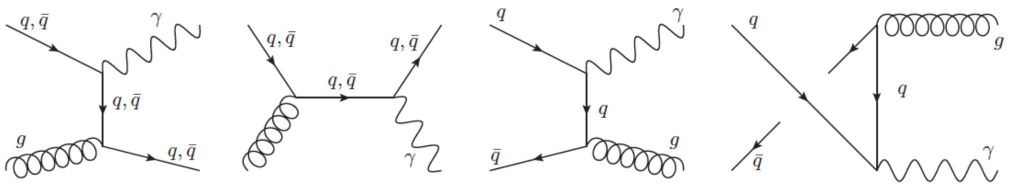

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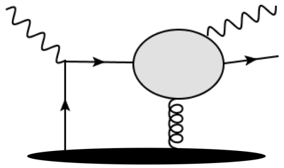

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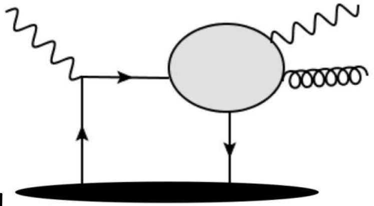


- New jet transport coefficients:

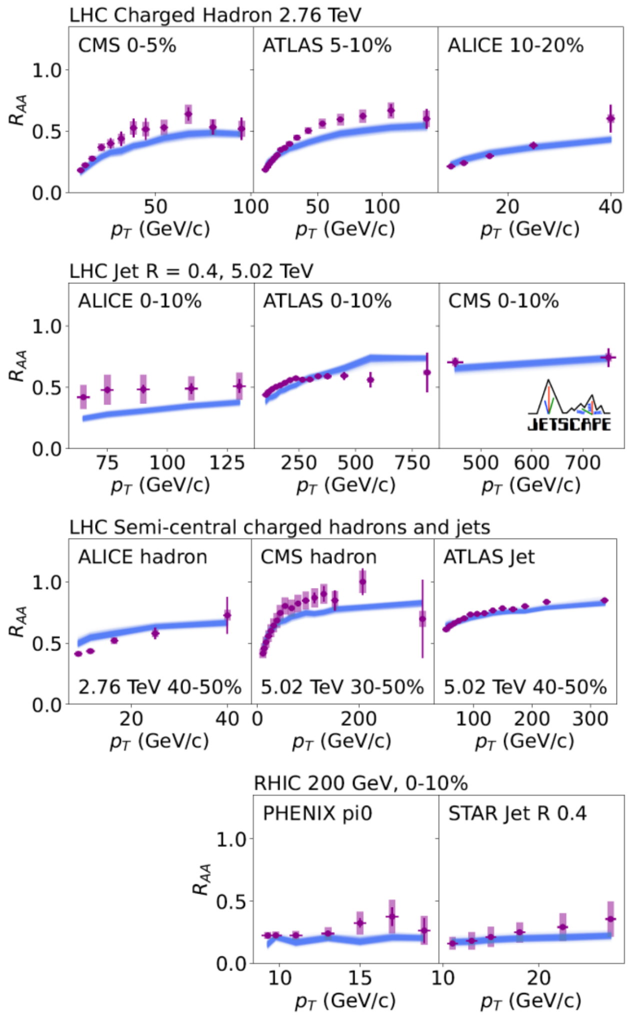
$$\hat{\mathcal{F}}_0 \sim \left\langle \bar{\psi}(\zeta^-, 0, \vec{0}_\perp) \frac{\gamma^+}{4} \psi(\zeta^-, \Delta z^-, \Delta \vec{z}_\perp) \right\rangle$$

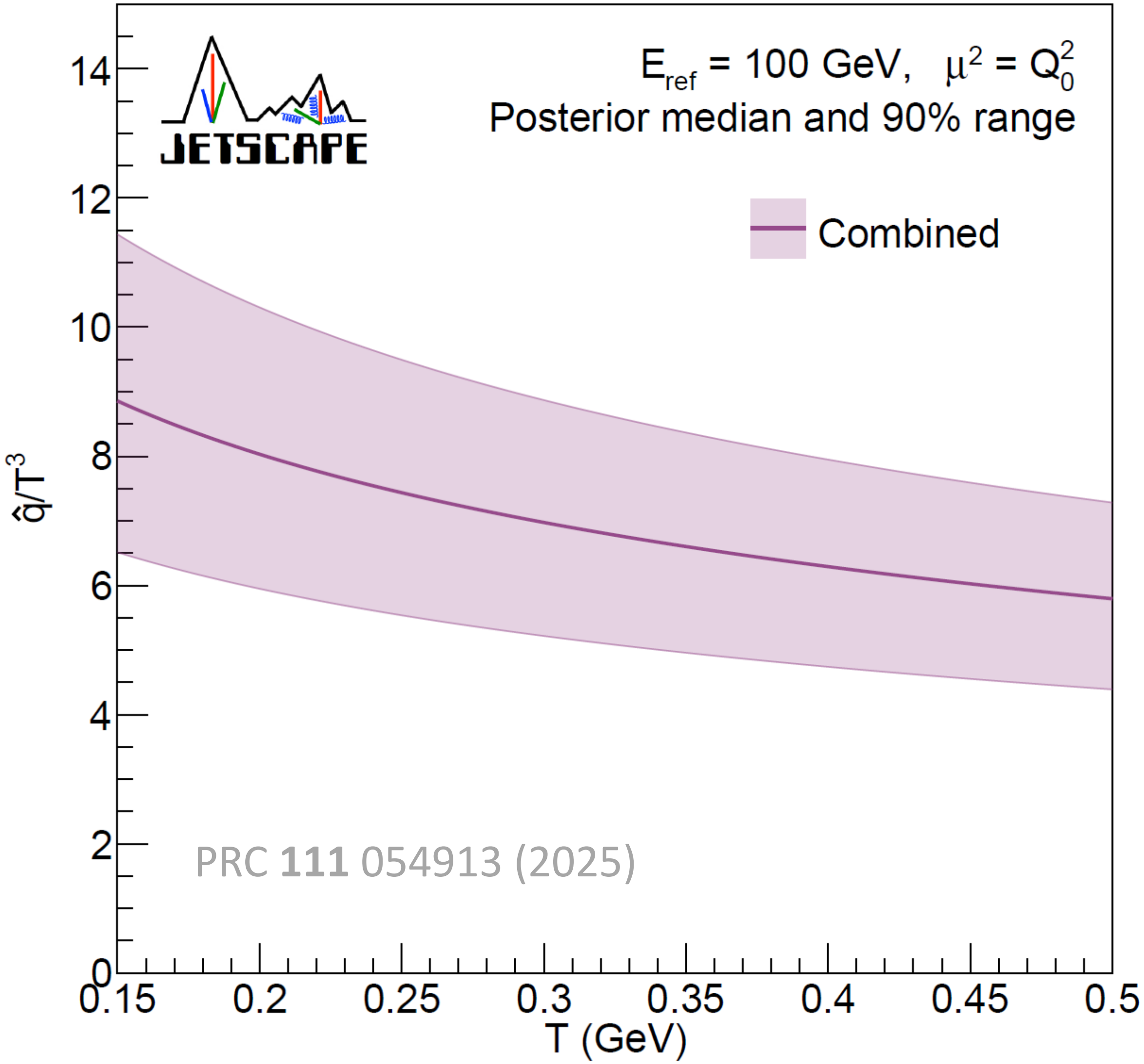
$$\hat{\mathcal{F}}_{L,1} \sim \left\langle [\partial^- \bar{\psi}(\zeta^-, 0, \vec{0}_\perp)] \frac{\gamma^+}{4} \psi(\zeta^-, \Delta z^-, \Delta \vec{z}_\perp) \right\rangle \qquad \hat{e} \sim \langle \mathrm{Tr}[i\partial^- A^+(\zeta^-, \Delta z^-, \Delta \vec{z}_\perp) A^+(\zeta^-, 0, \vec{0}_\perp)] \rangle$$

$$\hat{\mathcal{F}}_{T,2} \sim \left\langle [\partial_\perp \bar{\psi}(\zeta^-, 0, \vec{0}_\perp)] \frac{\gamma^+}{4} [\partial_\perp \psi(\zeta^-, \Delta z^-, \Delta \vec{z}_\perp)] \right\rangle \qquad \hat{q} \sim \langle \mathrm{Tr}[\partial_\perp A^+(\zeta^-, \Delta z^-, \Delta \vec{z}_\perp) \partial_\perp A^+(\zeta^-, 0, \vec{0}_\perp)] \rangle$$

Phenomenological implications of $\hat{\mathcal{F}}_i$

- Recent breakthrough: JETSCAPE constraints on $\hat{q}$ using multiscale (MATTER+LBT) jet-medium simulations and multiple observables across many experiments.





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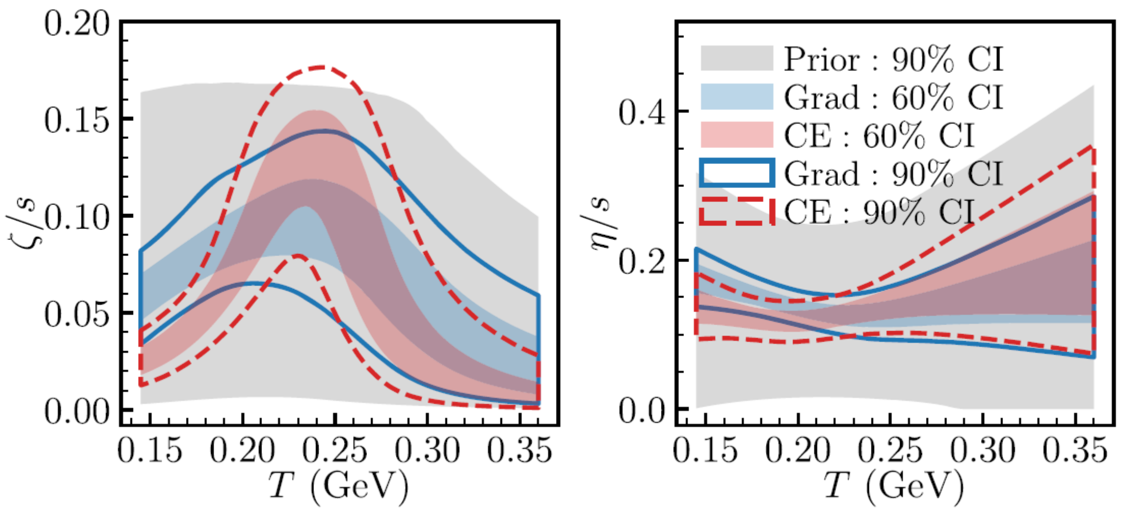
$$\eta = gaussian\ process\ for\ the\ model$$

$$y_{\mathrm{exp}} = \eta_{mod}$$



PLB **874** 140243 (2026)

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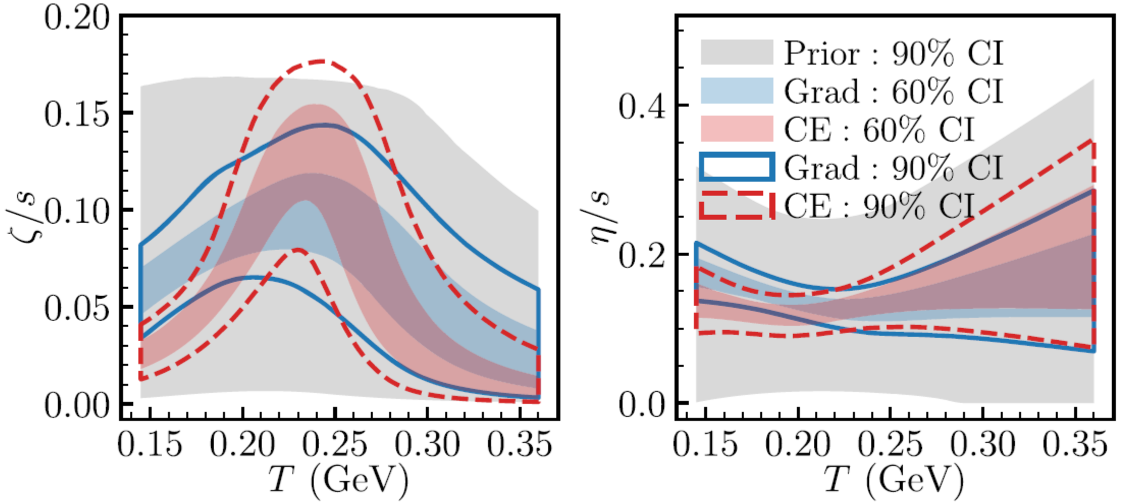

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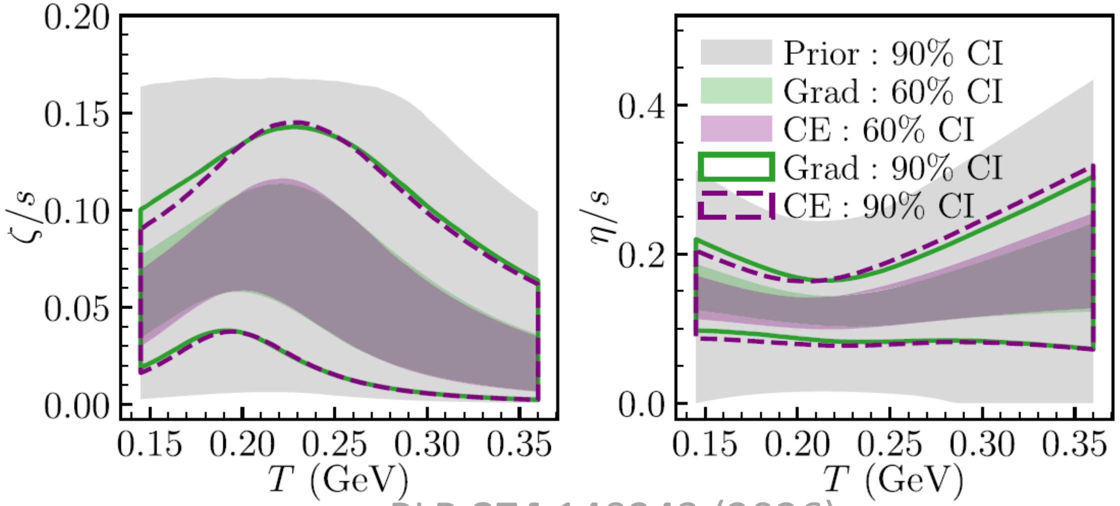
$\delta_{MD} = gaussian\ process\ for\ the\ model\ discrepancy$

$y_{\text{exp}} = \eta_{mod} + \delta_{MD}$



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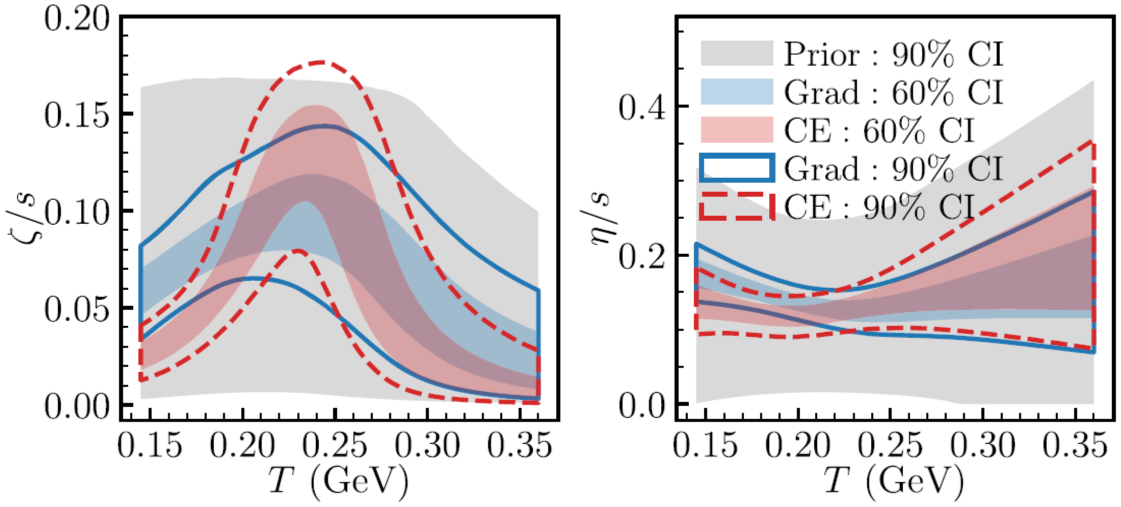

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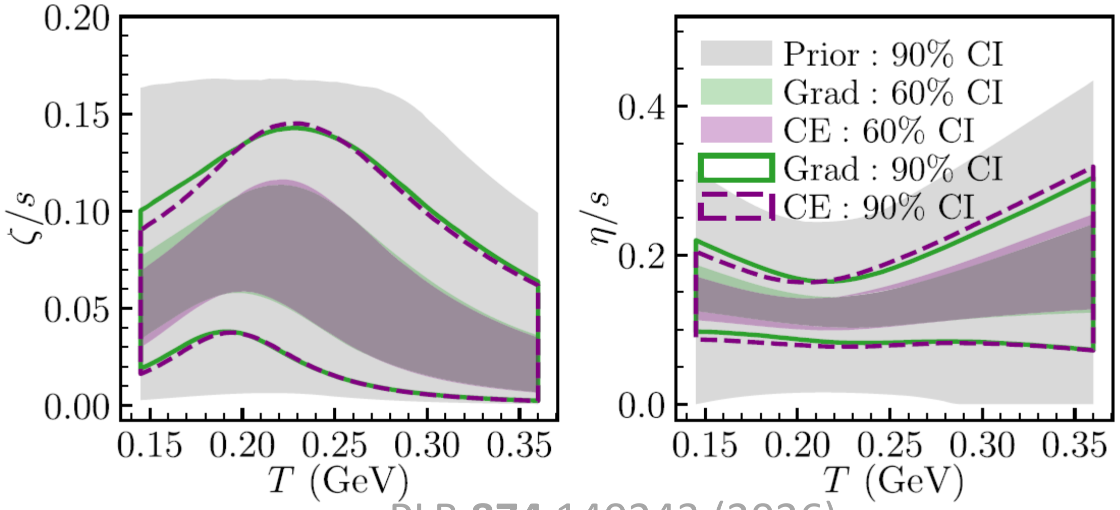

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- Using δ it may be possible to extract $\hat{q}$ while minimizing theory bias owing to *lack* of $\hat{\mathcal{F}}_i$.

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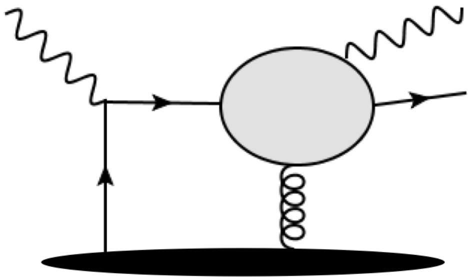
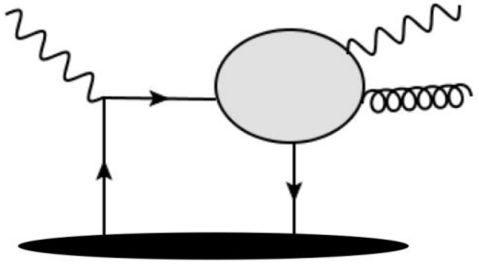
- Using δ to account for the lack of $\hat{\mathcal{F}}_i$ is *unsatisfactory* as $\hat{\mathcal{F}}_i$ is sensitive to poorly known, and *fundamentally interesting (!)*, physics of **flavor hydrodynamization**.
- Better approach is to treat $\hat{\mathcal{F}}_i$ like $\hat{q}$ inside of multiscale jet evolution simulations, so we need:

$\hat{q}$ *and* $\hat{e}$:

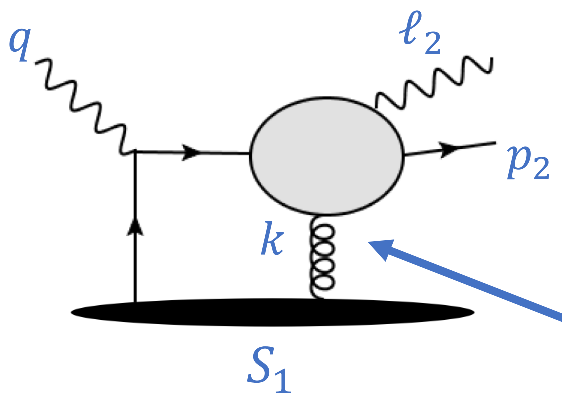


$\hat{\mathcal{F}}_i$:

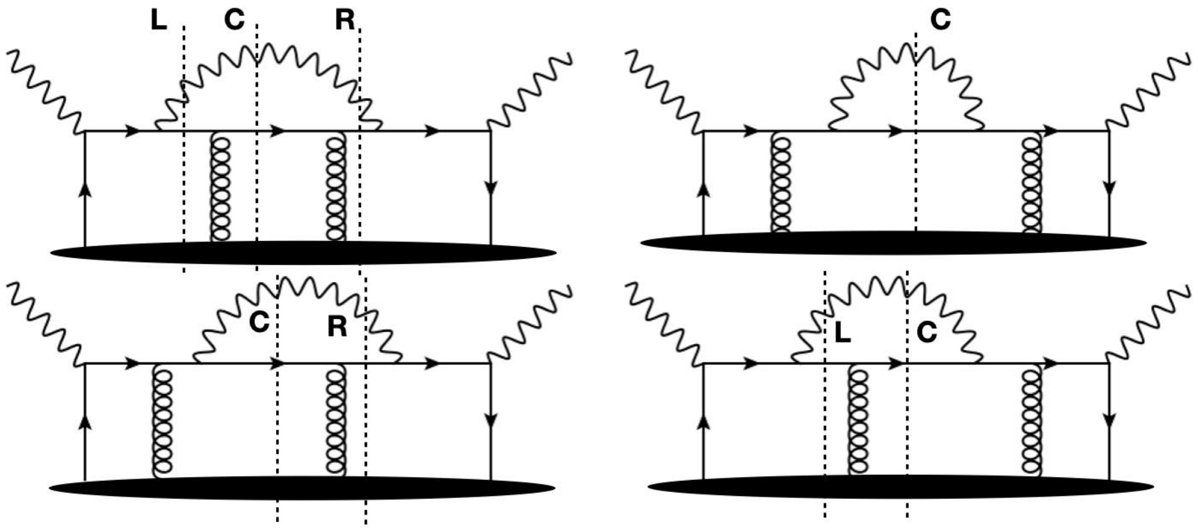


DIS in nuclear matter

- Jet-medium photon production at NLO (at high Q^2):



Medium-modified EM radiation



[Kumar & Vujanovic, PRC **112**, 025204 (2025)]

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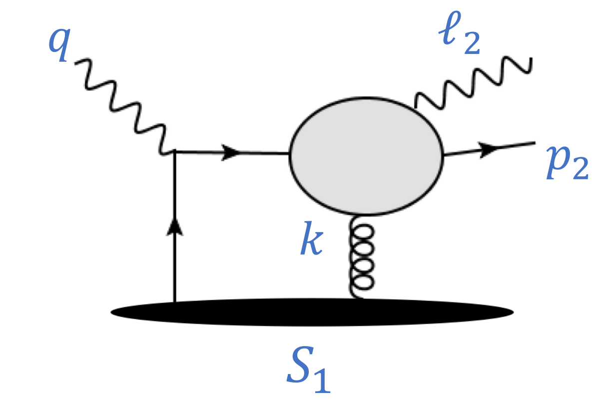
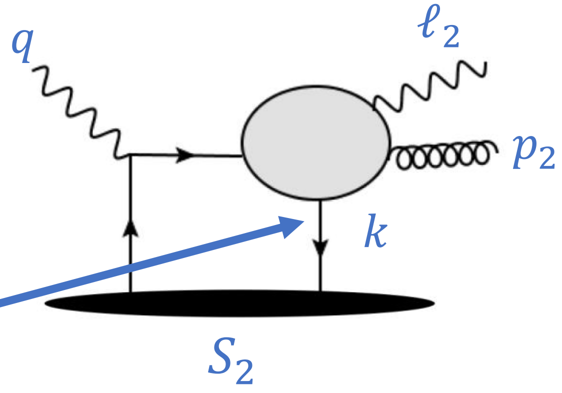
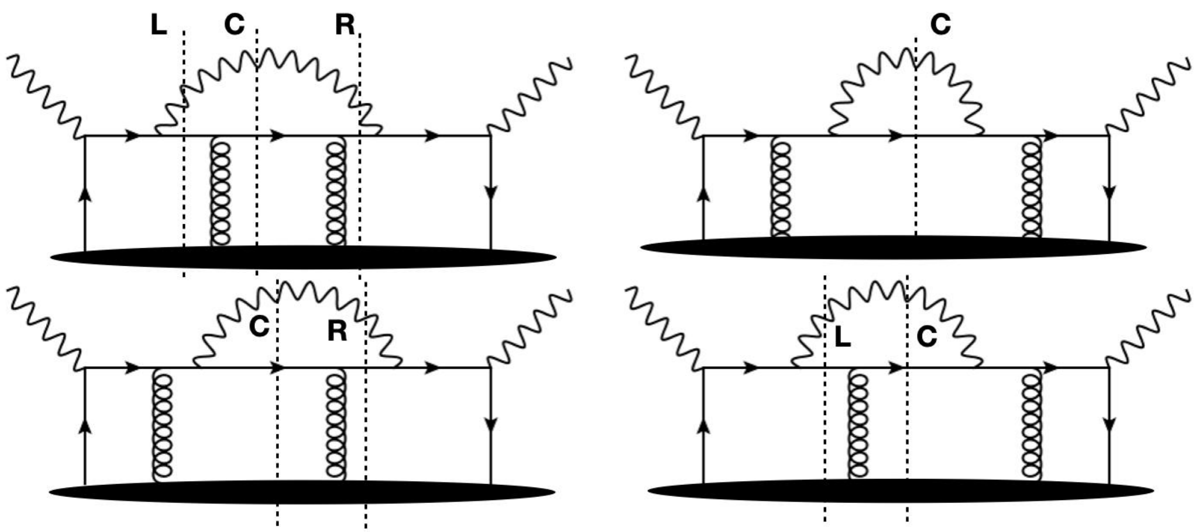
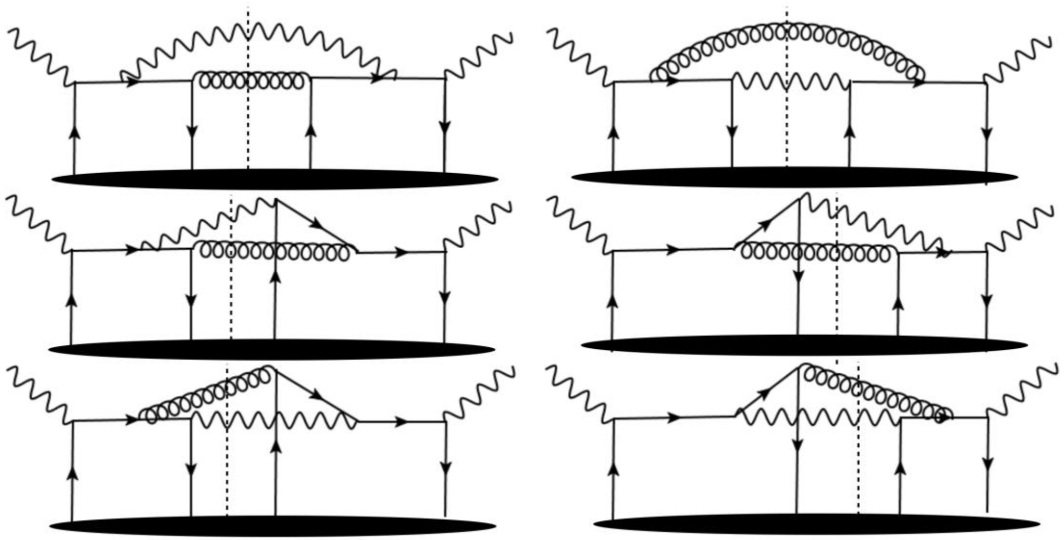




Medium-induced EM radiation ⇒ solely in-medium enhancement!

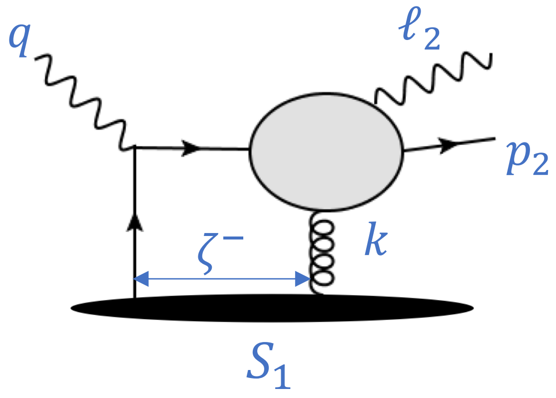




[Kumar & Vujanovic, PRC **112**, 025204 (2025)]

DIS in nuclear matter: the scattering kernels S_i

- The hadronic tensor:



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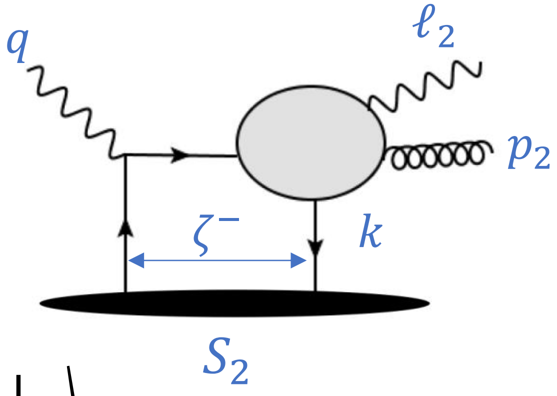

$$W_i^{\mu\nu} = \sum_f 2\left[-g_{\perp\perp}^{\mu\nu}\right] e_f^2 \underbrace{\int d(\Delta X^-) e^{i\Delta X^-\left(q^+ - \frac{M^2}{2q^-}\right)} \left\langle P \left| \bar{\psi}_f(\Delta X^-) \frac{\gamma^+}{4} \psi_f(0) \right| P \right\rangle}_{\text{nPDF}} K_i$$

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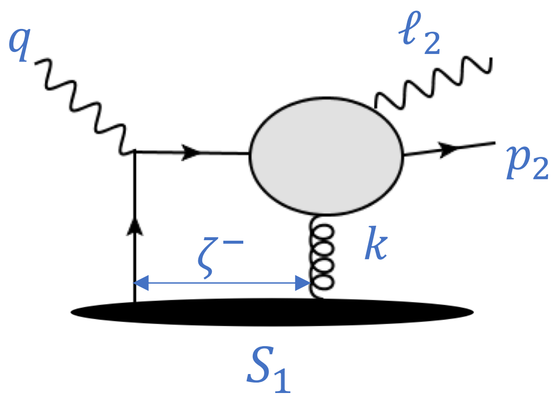

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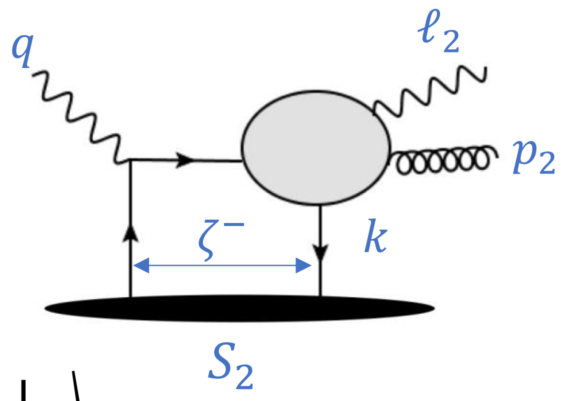

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$$K_i = e^2 e_f^2 g_s^2 C_i \int \frac{dy}{2\pi} \frac{d^2\ell_{2\perp}}{(2\pi)^2} d\zeta^- \int d(\Delta z^-) d^2(\Delta z_\perp) \frac{d^2 k_\perp}{(2\pi)^2} e^{-i\Delta z^- \mathcal{H}_M^{(\ell_2,p_2)}} e^{i\vec{k}_\perp\cdot\Delta\vec{z}_\perp} \theta(\zeta^-) \langle P_{A-1}|O_i|P_{A-1}\rangle S_i\left(\vec{\ell}_2, \vec{k}\right)$$

$$C_1 = 1 \qquad O_1 = \mathrm{Tr}\left[A^+(\zeta^-, \Delta z^-, \Delta\vec{z}_\perp) A^+\left(\zeta^-, 0, \vec{0}_\perp\right)\right] \qquad \mathcal{H}_M^{(\ell_2,p_2)} = \ell_2^+ + p_2^+ - \frac{M^2}{2q^-}$$

$$C_2 = C_f N_c \qquad O_2 = \bar{\psi}_f\left(\zeta^-, 0, \vec{0}_\perp\right) \frac{\gamma^+}{4} \psi_f(\zeta^-, \Delta z^-, \Delta\vec{z}_\perp) \qquad \mathcal{H}_M^{(\ell_2,p_2)} = \frac{\ell_{2\perp}^2 - yM^2}{2yq^-} + \frac{(\ell_{2\perp} - k_\perp)^2 + M^2}{2q^-(1 - y + \eta y)}$$

DIS in nuclear matter: the scattering kernels S_i

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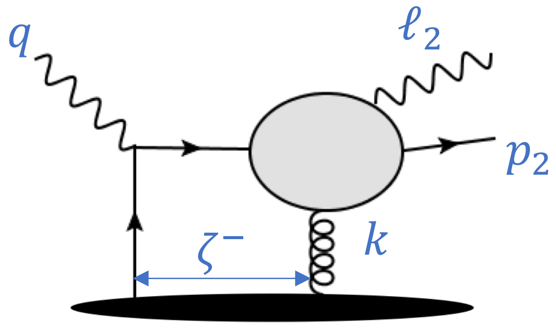
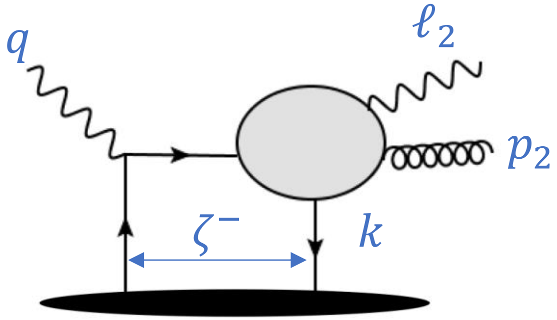


S_1

[Kumar & Vujanovic, PRC **112**, 025204 (2025)]



S_2

$$W_i^{\mu\nu} = \sum_f 2\left[-g_{\perp\perp}^{\mu\nu}\right] e_f^2 \int d(\Delta X^-) e^{i\Delta X^- \left(q^+ - \frac{M^2}{2q^-}\right)} \left\langle P \left| \bar{\psi}_f(\Delta X^-) \frac{\gamma^+}{4} \psi_f(0) \right| P \right\rangle K_i$$

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$$S_i\left(\vec{\ell}_2, k^-, \vec{k}_\perp\right) = S_i\left(\vec{\ell}_2, k^- = 0, \vec{k}_\perp = 0\right) + \left.\frac{\partial S}{\partial k^-}\right|_{k^-=0} k^- + \left.\frac{\partial S}{\partial k_\perp^\rho}\right|_{k_\perp=0} k_\perp^\rho + \frac{1}{2!}\left[\left.\frac{\partial^2 S}{\partial k^{-2}}\right|_{k^-=0} (k^-)^2 + \left.\frac{\partial^2 S}{\partial k_\perp^\rho \partial k_\perp^\sigma}\right|_{k_\perp=0} k_\perp^\rho k_\perp^\sigma\right] + \cdots$$

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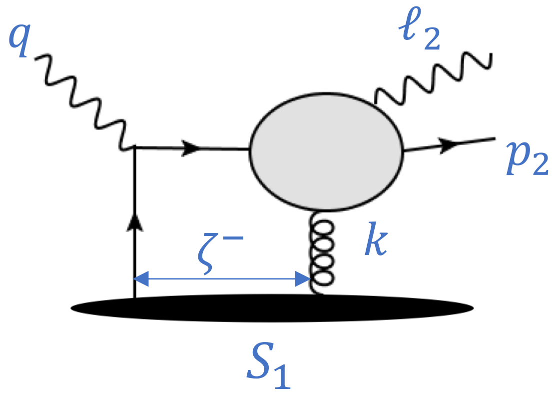

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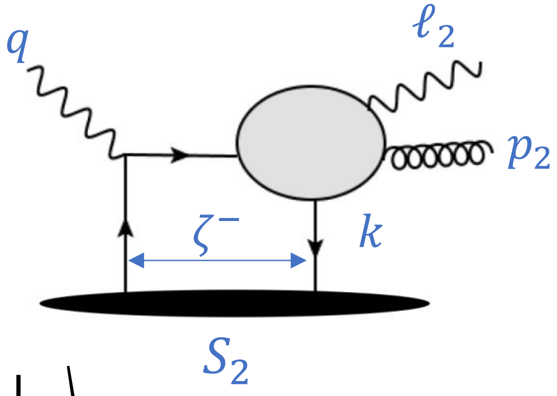

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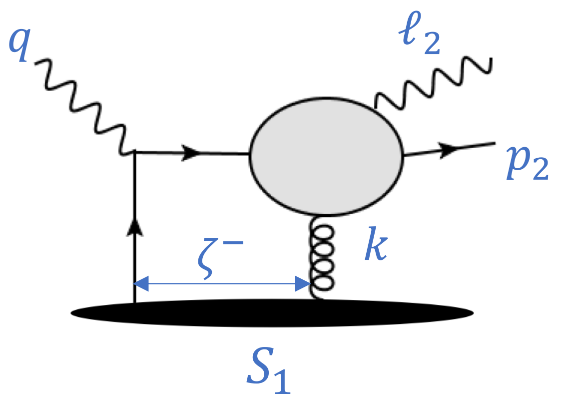

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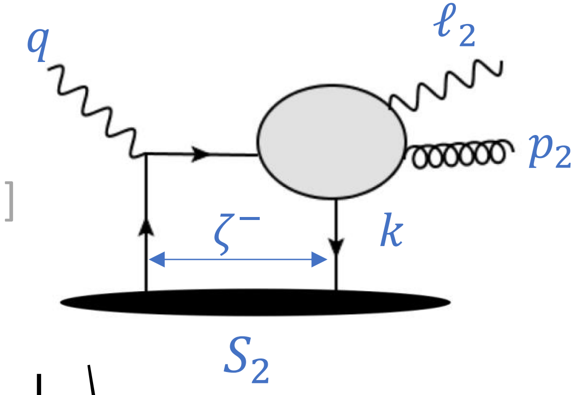

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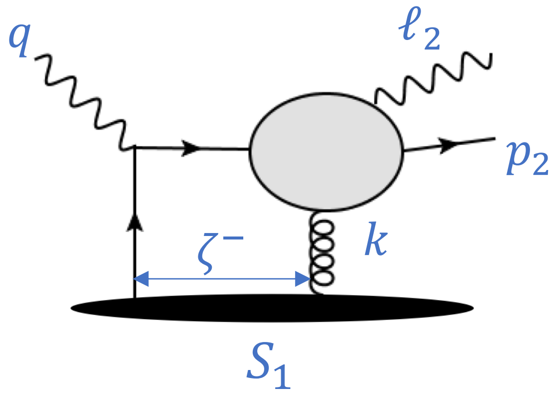
$$K_i = e^2 e_f^2 g_s^2 C_i \int \frac{dy}{2\pi} \frac{d^2\ell_{2\perp}}{(2\pi)^2} d\zeta^- \left\{ R_{(i;0)}^{(a;b,c)} \hat{O}_{(i;0)} + \left[\frac{1}{2!} R_{(i;T,2)}^{(a;b,c)} \hat{O}_{(i;T,2)} + \cdots \right] + \left[R_{(i;L,1)}^{(a;b,c)} \hat{O}_{(i;L,1)} + \frac{1}{2!} R_{(i;L,2)}^{(a;b,c)} \hat{O}_{(i;L,2)} + \cdots \right] \right\}$$

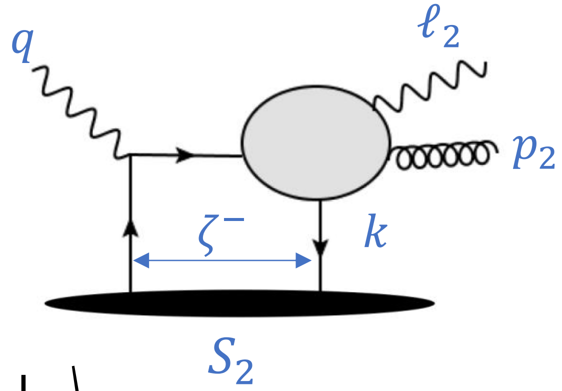
- The super script $(a;b,c)$ lables the reaction $a \to b + c$, i.e. $q \to q + \gamma$, $q \to g + \gamma$ and sim. for $\bar{q}$.
- R is the perturbative portion to the scattering kernel, while $\hat{O}$ is the non-perturbative two-point function.

DIS in nuclear matter: the scattering kernels S_i

- The hadronic tensor:



[Kumar & Vujanovic, PRC **112**, 025204 (2025)]



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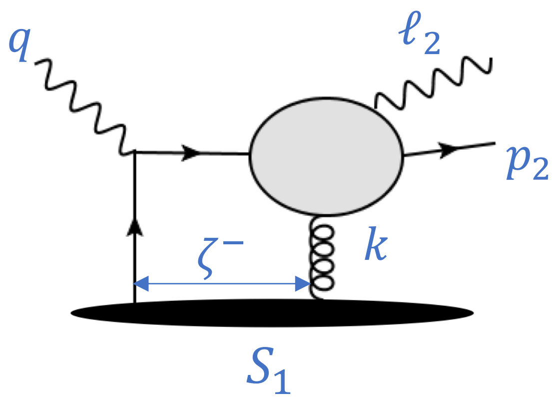
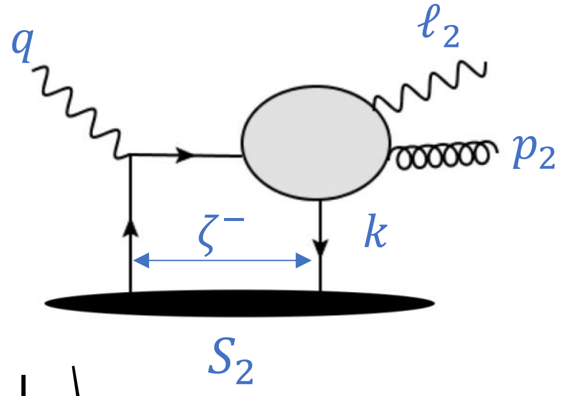
- The super script $(a; b, c)$ lables the reaction $a \to b + c$, i.e. $q \to q + \gamma$, $q \to g + \gamma$ and sim. for $\bar{q}$.
- The L and T subscripts in $\hat{O}$ label the longitudinal and transverse jet energy loss transport coefficients.
  - $\hat{O}_{i=1}$ is related to gluon TMD-PDFs (via $\ell_{2\perp}$- phase factor), $\hat{e} = \hat{O}_{(1;L,1)} \sim \langle \mathrm{Tr}[i\partial^- A^+(\zeta^-, \Delta z^-, \Delta\vec{z}_\perp) A^+(\zeta^-, 0, \vec{0}_\perp)] \rangle$ and $\hat{q} = \hat{O}_{(1;T,2)}$
  - $\hat{O}_{i=2}$ is related to quark TMD-PDFs

DIS in nuclear matter: the scattering kernels S_i

- The hadronic tensor:



[Kumar & Vujanovic, PRC **112**, 025204 (2025)]



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- Recall that $\widehat{\mathrm{O}}_{(1;0)} \sim \langle \mathrm{Tr}[A^+ A^+] \rangle$ does not contribute to energy loss; it is part of the quark nuclear PDF.
- $\hat{O}_{(2;0)}$ contributes to jet energy loss.

$$\hat{O}_{(2;0)} = \hat{\mathcal{F}}_0 = g_s^2 \int \frac{dy}{2\pi} \frac{d^2\ell_{2\perp}}{(2\pi)^2} d\zeta^- \int d(\Delta z^-) d^2(\Delta z_\perp) \frac{d^2 k_\perp}{(2\pi)^2} e^{-i\Delta z^- \mathcal{H}_0^{(\ell_2,p_2)}} e^{i\vec{k}_\perp \cdot \Delta \vec{z}_\perp} \theta(\zeta^-) \left\langle P_{A-1} \left| \bar{\psi}(\zeta^-, 0, \vec{0}_\perp) \frac{\gamma^+}{4} \psi(\zeta^-, \Delta z^-, \Delta\vec{z}_\perp) \right| P_{A-1} \right\rangle$$

Taylor expanded perturbative scattering kernels

- Transverse momentum broadening $R_{(i;T,2)}$ at next to leading twist, for massless incoming quarks

$$\left.\frac{\partial^2 S_i}{\partial k_\perp^2}\right|_{k_\perp=0} = R_{(i;T,2)}$$

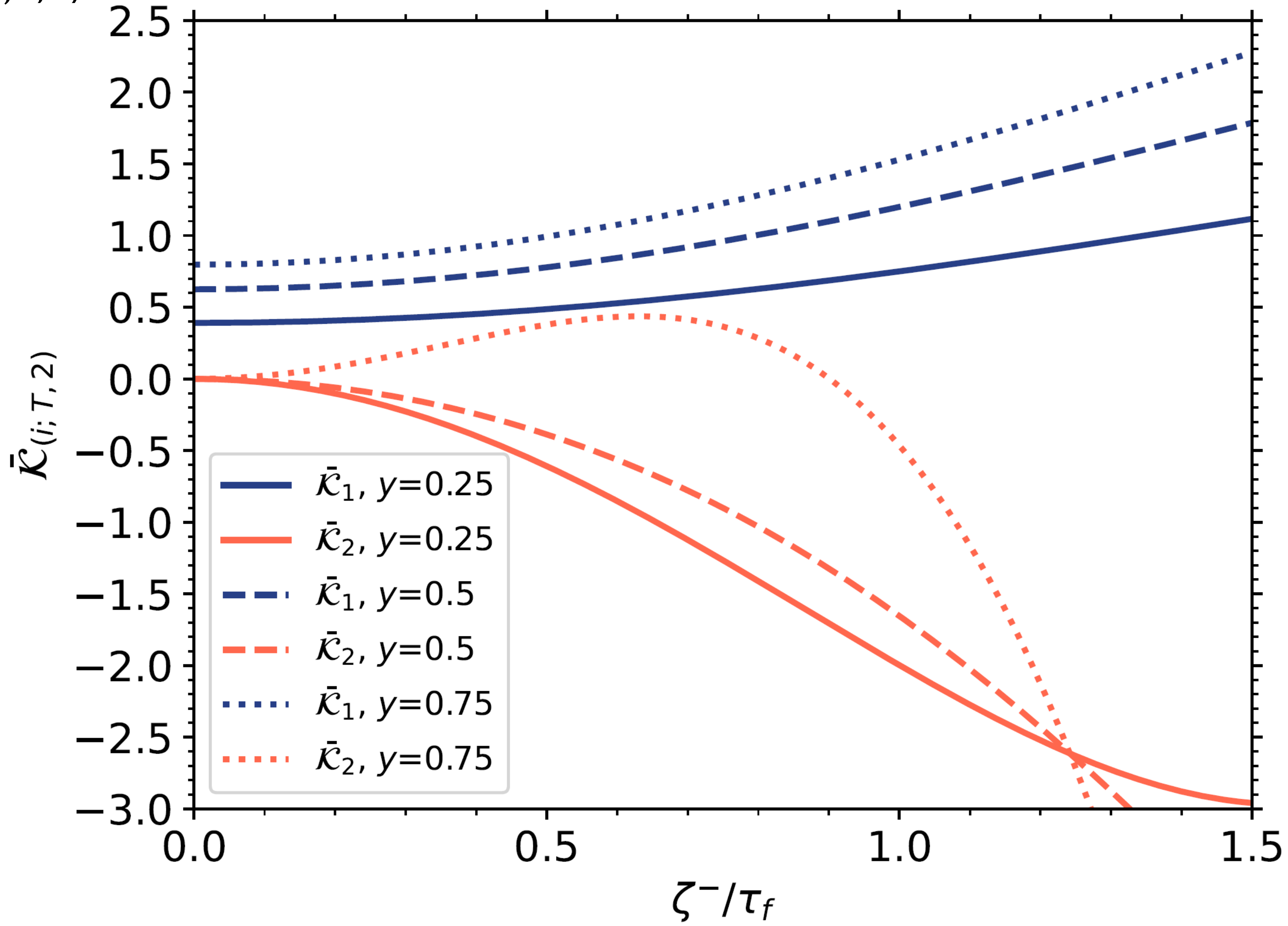
- Glauber gluons contribution: $R_{(1;T,2)}$

$$R_{(1;T,2)} = \frac{4}{\ell_{2\perp}^4}\bar{\mathcal{K}}_{(1;T,2)}$$

- Glauber quarks contribution: $R_{(2;T,2)}$

$$R_{(2;T,2)} = \frac{4}{yq^-\ell_{2\perp}^4}\bar{\mathcal{K}}_{(2;T,2)}$$

- The fact that $\bar{\mathcal{K}}_2(\zeta^-)$ goes negative, is not too concerning…



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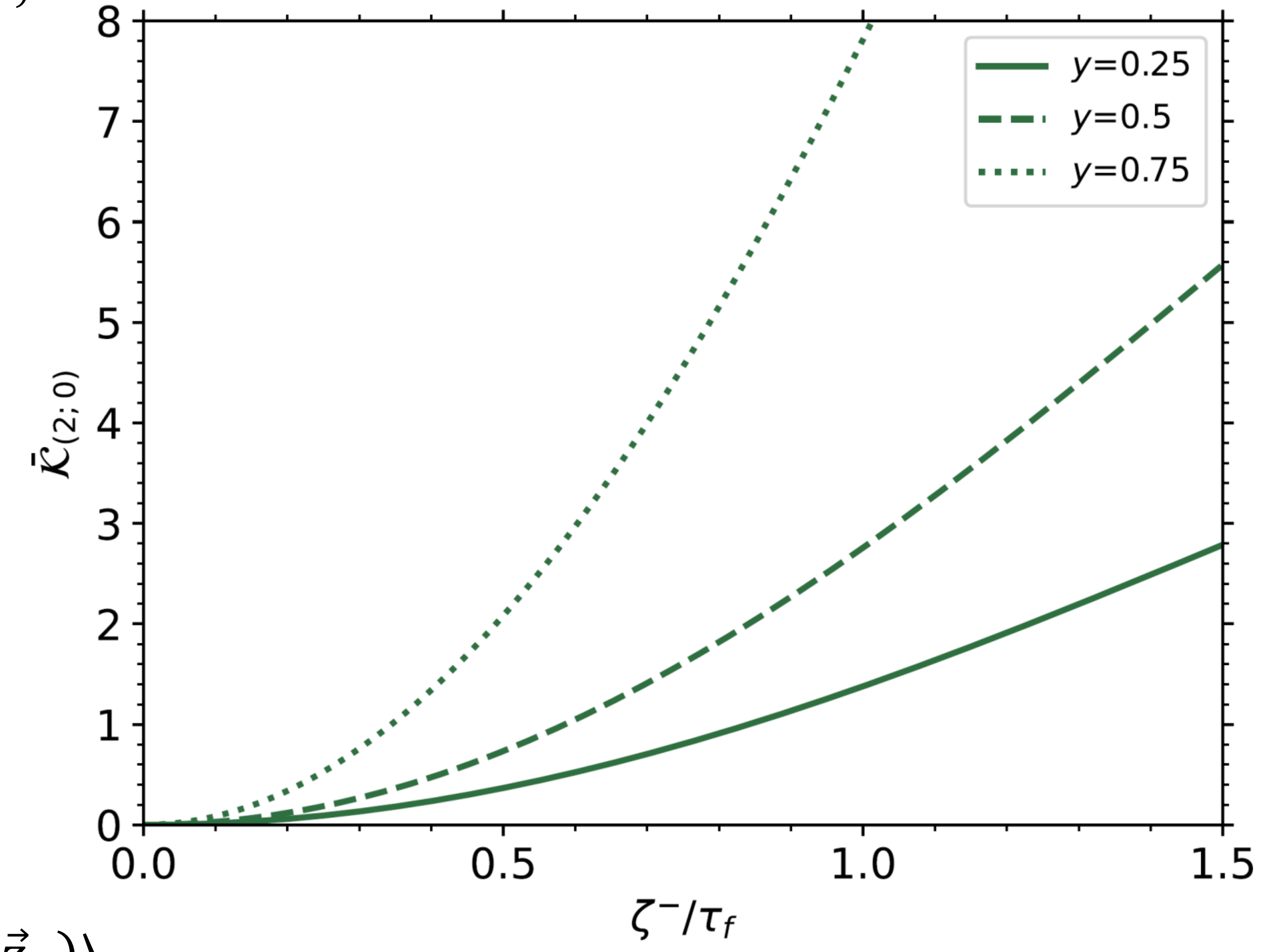
- The fact that $\bar{\mathcal{K}}_2(\zeta^-)$ goes negative, is not too concerning, as one must add

$$R_{(2;0)} = S_2(0,\vec{0}) = \frac{\bar{\mathcal{K}}_{(2;0)}}{(yq^-)\ell_{2\perp}^2}\hat{\mathcal{F}}_0,$$

$$\hat{\mathcal{F}}_0 \sim \sum_f \langle\bar{\psi}_f(\zeta^-,0,\vec{0}_\perp)\frac{\gamma^+}{4}\psi_f(\zeta^-,\Delta z^-,\Delta\vec{z}_\perp)\rangle.$$



Taylor expanded perturbative scattering kernels

- Longitudinal drag $R_{(i;L,1)}$ at next to leading twist, for massless incoming quarks

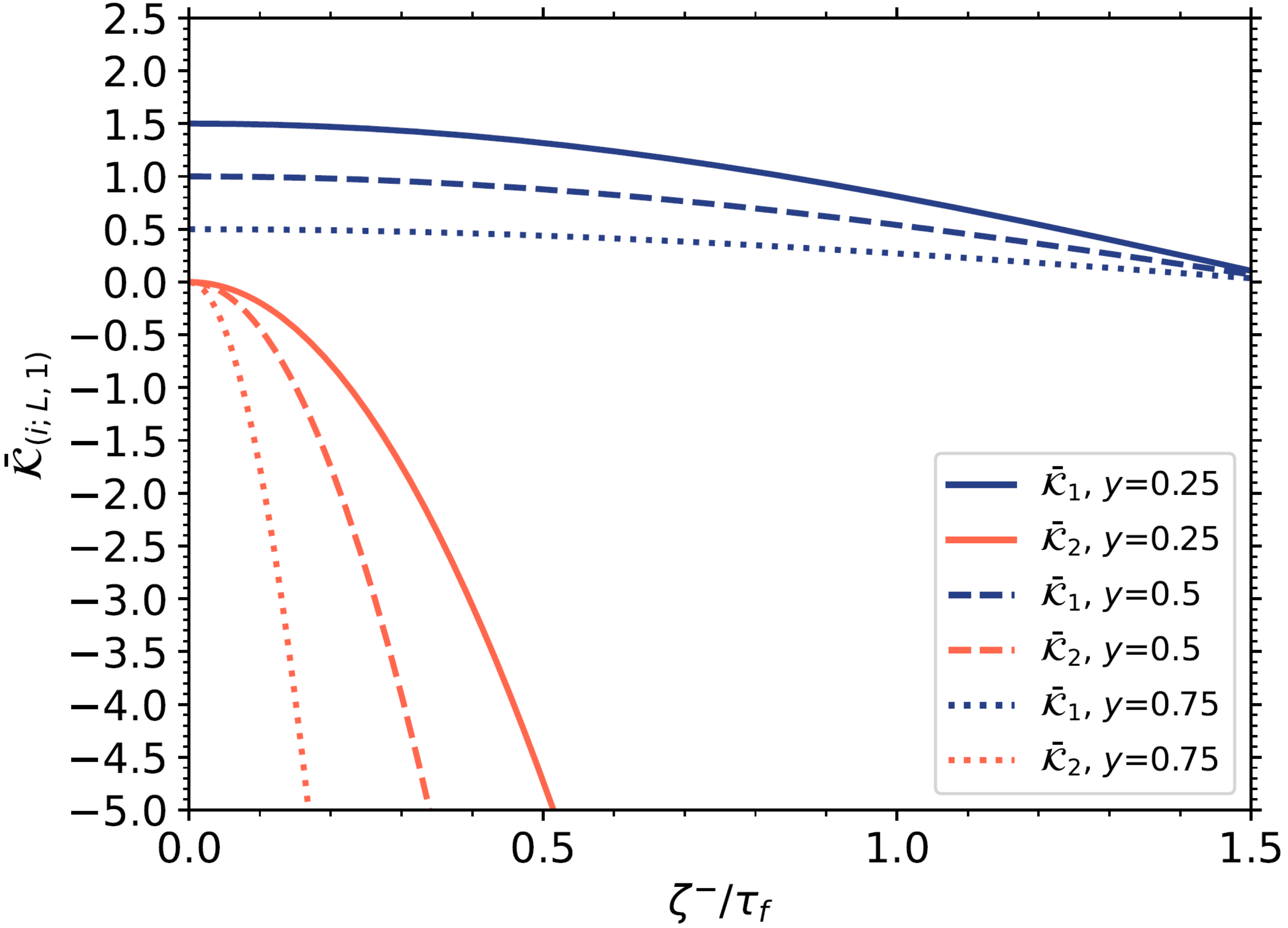
$$\frac{\partial S_i}{\partial k^-}\Big|_{k^-=0} = R_{(i;L,1)}$$

- Glauber gluons contribution: $R_{(1;L,1)}$

$$R_{(1;L,1)} = \frac{4}{q^- \ell_{2\perp}^2} \bar{\mathcal{K}}_{(1;T,2)}$$

- Glauber quarks contribution: $R_{(2;L,1)}$

$$R_{(2;L,1)} = \frac{1}{(yq^-)q^- \ell_{2\perp}^2} \bar{\mathcal{K}}_2$$

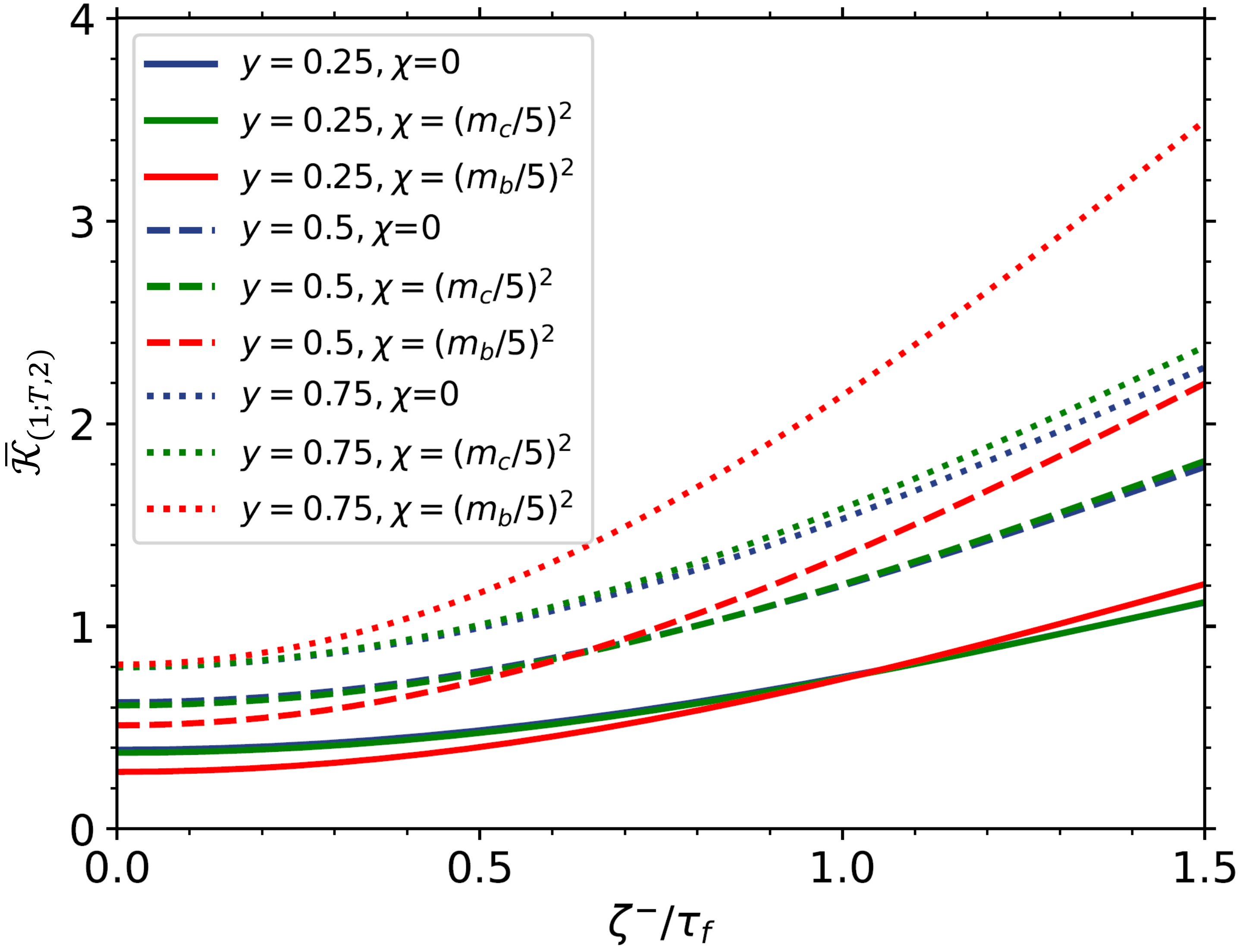


Taylor expanded perturbative scattering kernels

- The mass dependence of transverse broadening

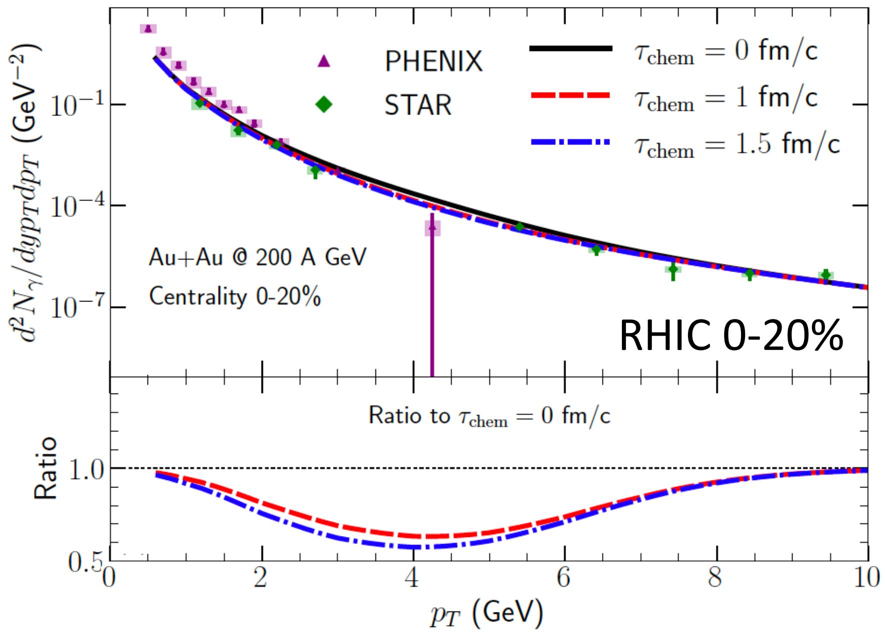
$$R_{(1;T,2)} = \frac{4}{\ell_{2\perp}^4 (1+\chi)^4} \bar{\mathcal{K}}_{(1;T,2)}$$

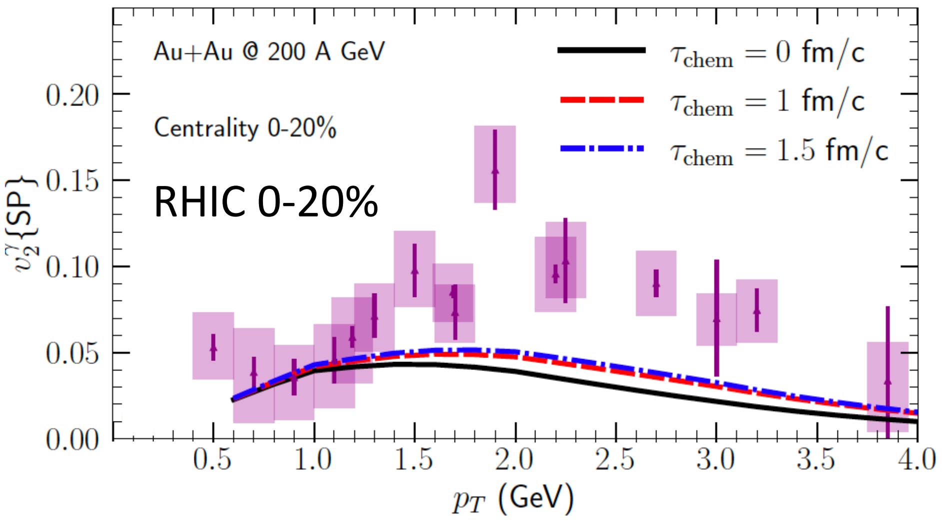
$$\chi = \frac{y^2 M^2}{\ell_{2\perp}^2}$$



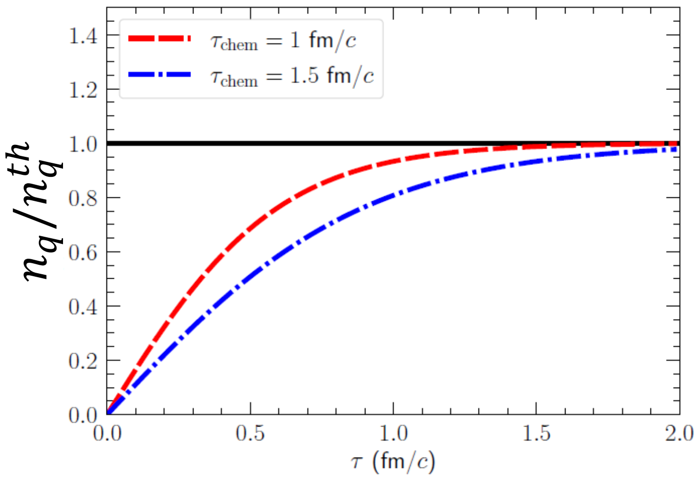
Photons and Flavor hydrodynamization

- The transition from glasma to QGP with thermal photons





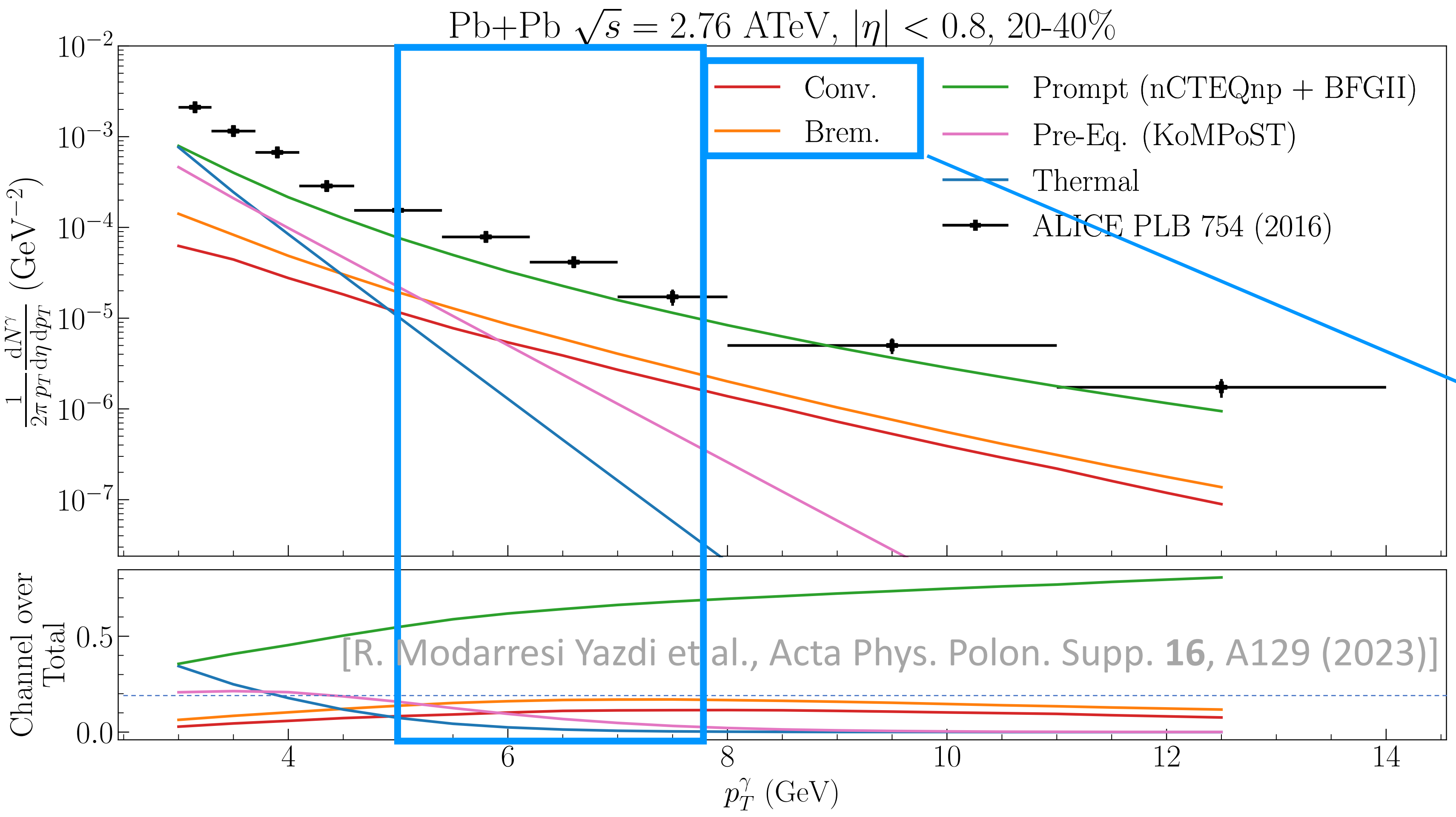
[C. Gale et al., Phys. Rev. C **105**, 014909 (2022)]



- Photons are sensitive dynamics of quarks production CGC → hydrodynamics.
- Need to include jet-medium photons and account for $\hat{\mathcal{F}}_i$.

Photon production at intermediate p_T

- MARTINI: Conversion and bremsstrahlung photons contribute significantly at intermediate p_T



Photons $5 < p_T < 8$ GeV:

- Total yield dominated by prompt photons
- Significant contribution from jet-medium ≈ 30 % of thermal
  - Conversion ≈ 12 %
  - Bremsstrahlung ≈ 18 %

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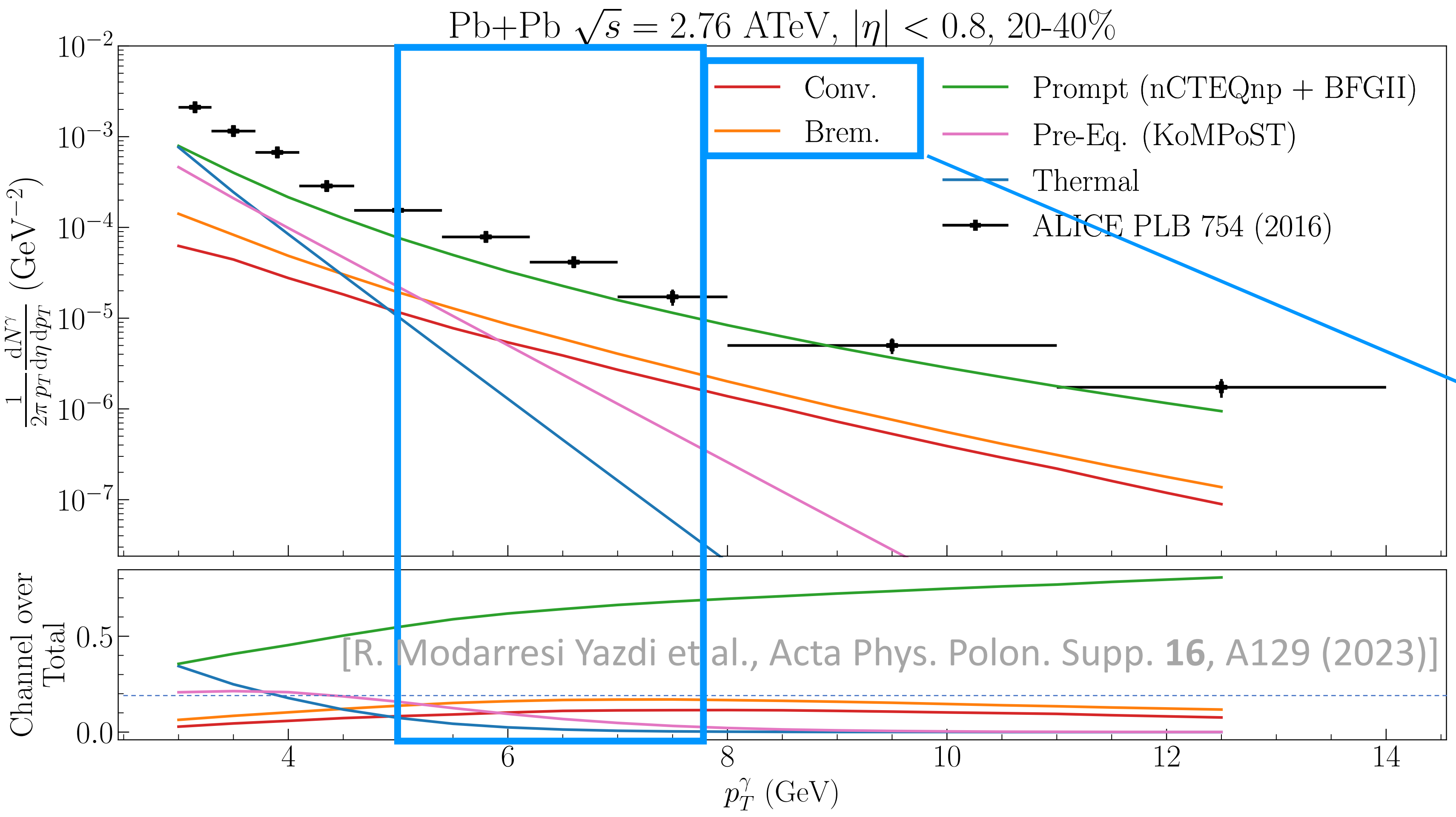

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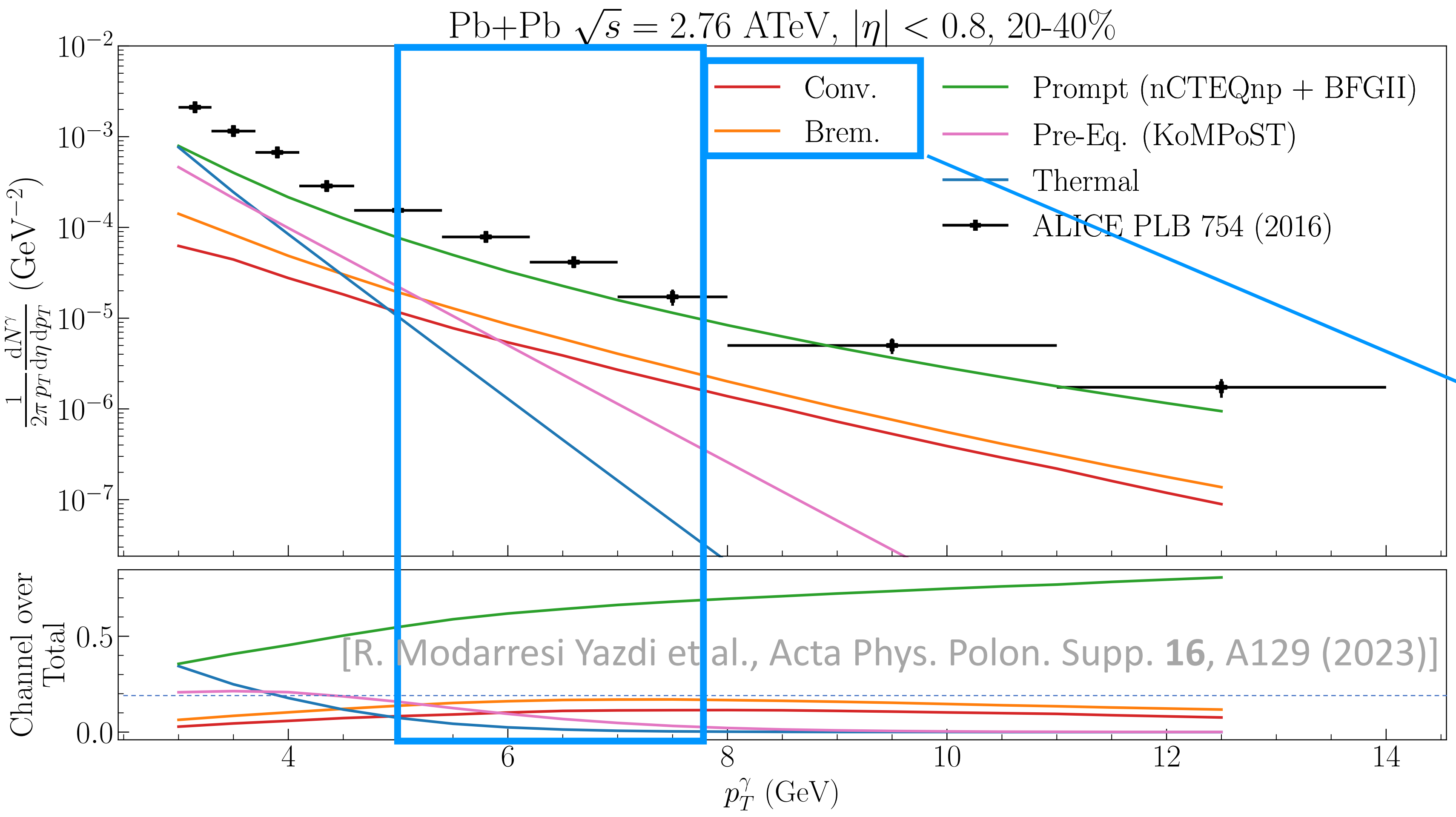

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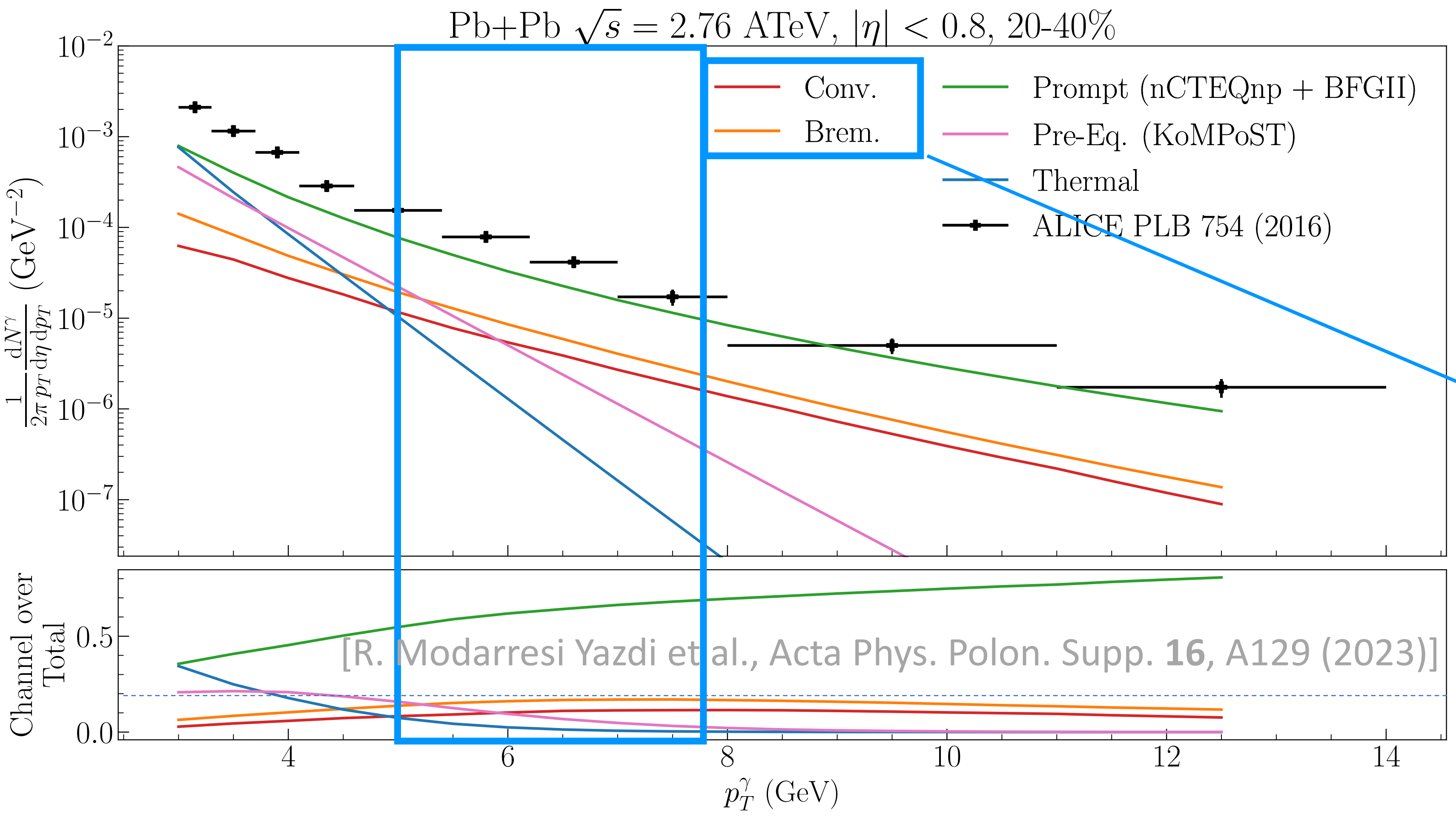

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- This is where our calculations come in.

- Jet-medium photons are directly sensitive to $\hat{q}$ and $\hat{\mathcal{F}}_i$, **avoiding** hadronization effects.
- Need to know $\hat{\mathcal{F}}_i$ to estimate the bias in the current Bayesian constraints on $\hat{q}$.

Conclusion & Outlook

- Photon production mechanism from all virtuality scales are now at hand.
- Having a comprehensive theoretical description of photons is a boon for
  - understanding photon-only observables (spectra, flow, etc.) needed to constrain "soft" transport coefficients (e.g. η/s, ζ/s, etc.)
  - understanding jet-medium photons (e.g. photon-triggered jets and jet substructure) and thus jet-medium transport coefficients. For recent developments in photon-triggered jet studies see e.g.
    C. Sirimanna et al., Phys. Rev. C **111**, 064911 (2025),
    Y. Tachibana et al., Phys. Rev. C **113**, 034910 (2026)

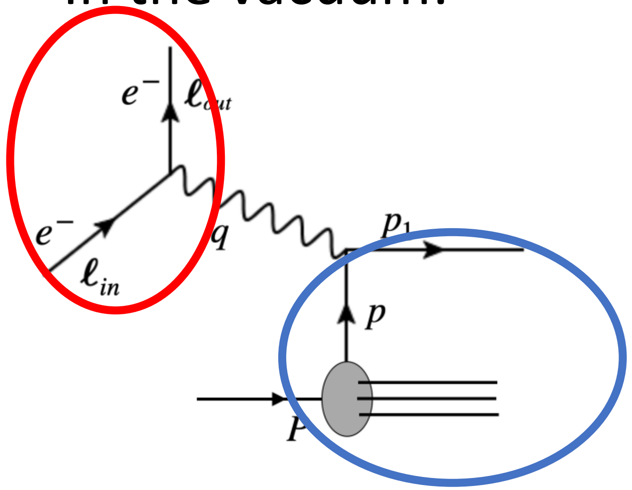
- More importantly, photons can deepen our understanding of how hydrodynamics is reached from the initial Glasma.
- These new directions can only be fully appreciated if Glauber quarks are accounted for in $q \to g + g$, $q \to q + \bar{q}'$ and $q \to q + q'$… covered by the next speaker

Thank you

Backup slides

Deep Inelastic Scattering (DIS)

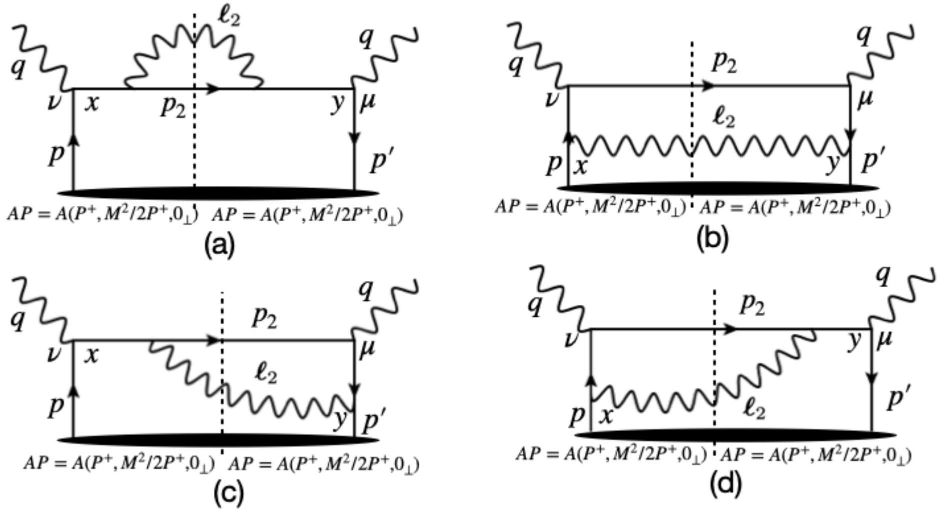
- In the vacuum:



$$\ell^0 \frac{d^3\sigma}{d^3\ell} = \frac{\alpha_{EM}^2}{2\pi s Q^4} L_{\mu\nu} W^{\mu\nu}$$

$$L^{\mu\nu} = \frac{1}{2}\mathrm{Tr}[(\ell_{in}\cdot\gamma)\,\gamma^\mu\,(\ell_{out}\cdot\gamma)\,\gamma^\nu]$$

$$W^{\mu\nu} = \sum_f 2[-g_{\perp\perp}^{\mu\nu}]e^2 e_f^2 g_s^2 \int d\Delta x^- e^{i\Delta x^-(q^+)} \left\langle P \left| \bar{\psi}_f(\Delta x^-)\frac{\gamma^+}{4}\psi_f(0) \right| P \right\rangle K_0$$



$$K_0 = \int \frac{dy}{2\pi}\frac{d^2\ell_{2\perp}}{(2\pi)^2} e^{-i\Delta x^- H_M^{(\ell_2)}} S_0(\ell_{2\perp})$$

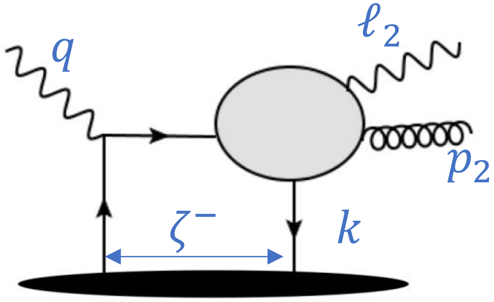
$$H_M^{(\ell_2)} = \frac{\ell_{2\perp}^2 + yM}{2y(1-y)q^-}$$

$$S_0(\ell_{2\perp}) = \frac{1+(1-y)^2}{y}\frac{[\ell_{2\perp}^2 + \kappa y^4 M^2]}{[\ell_{2\perp}^2 + y^2 M^2]^2}$$

$$\kappa = \frac{1}{1+(1-y)^2}$$

DIS inside the QGP: the scattering kernel S_i

- Glauber-quark scattering kernel:



$$S_2 = \left[\frac{1+(1-y)^2}{y}\right]\left\{\frac{2-2\cos\left[\mathcal{G}_0^{(\ell_2)}\zeta^-\right]}{(1-y+\eta y)q^-\ell_{2\perp}^2}\right\}$$
$$+\left[\frac{1+y^2(1-\eta)^2}{1-y(1+\eta)}\right]\left\{\frac{2-2\cos\left[\mathcal{G}_0^{(\ell_2)}\zeta^-\right]}{(\ell_{2\perp}-k_\perp)^2 yq^-}\right\}$$
$$-\left[\frac{1+(1-y)^2+\eta y(2-y)}{y}\right]\left[\frac{(1+\eta y)\ell_{2\perp}^2 - yk_\perp\cdot\ell_{2\perp}+\kappa M^2y^4}{(\ell_2^2+M^2y^2)J_1}\right]\left\{2-2\cos\left[\mathcal{G}_0^{(\ell_2)}\zeta^-\right]\right\}$$

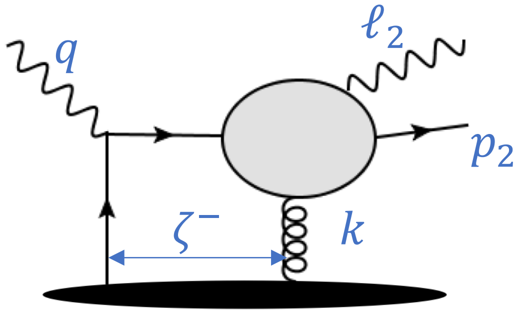
$$y=\frac{\ell_2^-}{q^-} \qquad \kappa=\frac{1}{1+(1-y)^2} \qquad J_1=[(1+\eta y)\ell_{2\perp}-yk_\perp]^2+M^2y^2$$

$$\eta=\frac{k^-}{\ell_{2\perp}^-} \qquad \mathcal{G}_0^{(\ell_2)}=\frac{\ell_{2\perp}^2}{2y(1-y)q^-}$$

[Kumar & Vujanovic, PRC 112, 025204 (2025)]

DIS inside the QGP: the scattering kernel S_i

- Glauber-gluon scattering kernel:



$$S_1 = \left[\frac{1+(1-y)^2}{y}\right]\left[\frac{\ell_{2\perp}^2 + \kappa M^2 y^4}{(\ell_{2\perp}^2 + M^2 y^2)^2}\right]\left\{1 - \cos\left[\mathcal{G}_M^{(\ell_2)}\zeta^-\right]\right\}$$
$$+ \left[\frac{(1+\eta y)^2 + (1-y+\eta y)^2}{y}\right]\left\{\frac{[(1+\eta y)\ell_{2\perp}^2 - y k_\perp]^2 + \kappa M^2 y^4}{J_1^2}\right\}$$
$$- \left[\frac{1+(1-y)^2 + \eta y(2-y)}{y}\right]\left[\frac{(1+\eta y)\ell_{2\perp}^2 - y k_\perp \cdot \ell_{2\perp} + \kappa M^2 y^4}{(\ell_2^2 + M^2 y^2) J_1}\right]\left\{2 - 2\cos\left[\mathcal{G}_M^{(\ell_2)}\zeta^-\right]\right\}$$

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[Kumar & Vujanovic, PRC 112, 025204 (2025)]