Two-gluon one-photon vertex in the presence of a magnetic field:

General structure and one-loop approximation in the intermediate field regime

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Acknowledgments

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Two-gluon one-photon vertex in a magnetic field and its explicit one-loop approximation in the intermediate field strength regime

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We find the general structure for the two-gluon one-photon vertex in the presence of a constant magnetic field. We show that, when accounting for the symmetries satisfied by the strong and electromagnetic interactions under parity, charge conjugation and gluon interchange, and for gluons and photons on mass-shell, there exist only three possible tensor structures that span the vertex. These correspond to external products of the polarization vectors for each of the particles in the vertex. We also explicitly compute the one-loop approximation to this vertex in the intermediate field strength regime, which is the most appropriate one to describe possible effects of the presence of a magnetic field to enhance photon emission during preequilibrium in peripheral relativistic heavy-ion collisions. We show that the most favored direction for the photon to propagate is in the plane transverse to the field, which is consistent with a positive contribution to v_2 and may help to understand the larger than expected elliptic flow coefficient measured in this kind of reaction.

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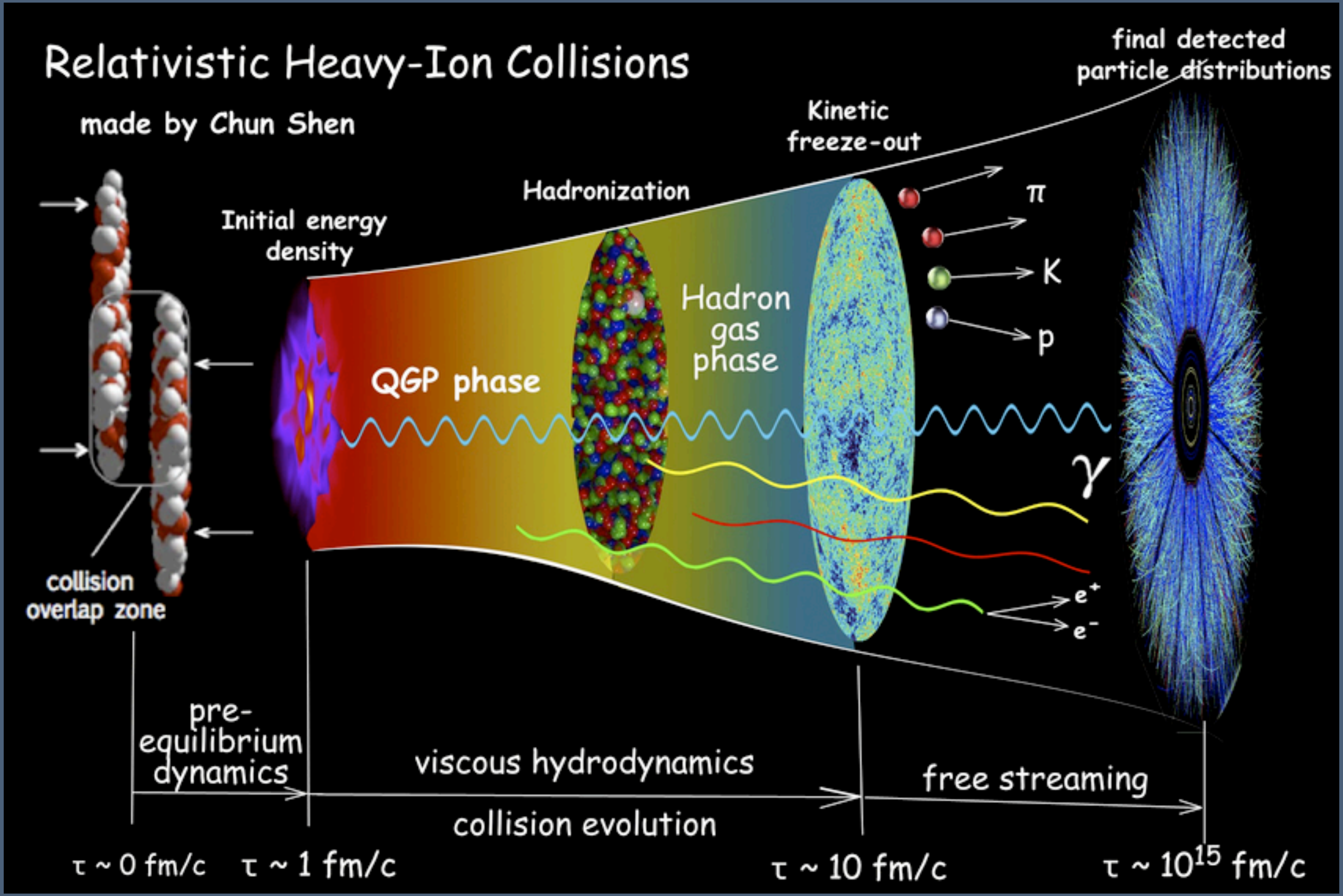
Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
Hadron gas phase
QGP phase
π
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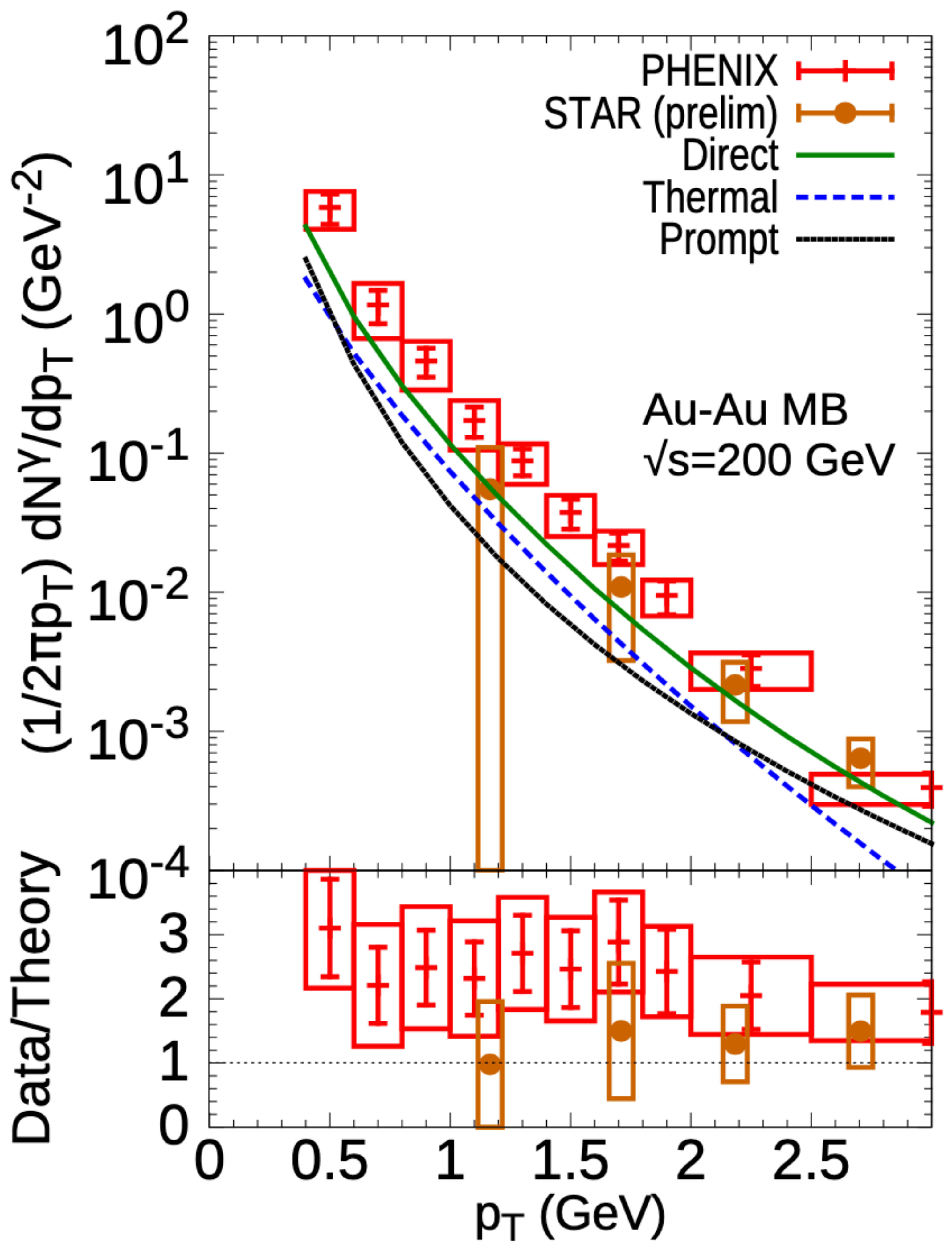
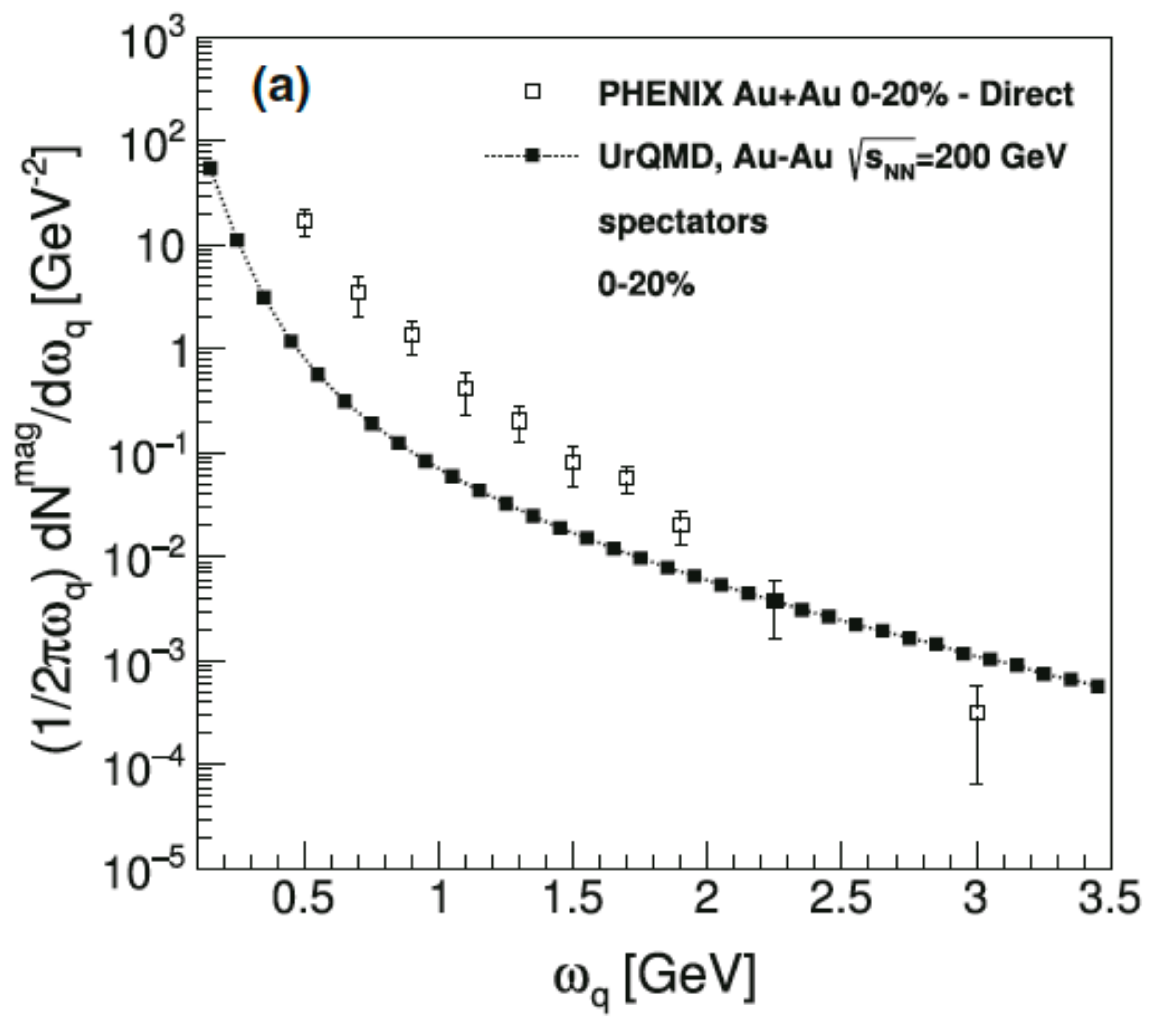
p
γ
e^+
e^-
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
$\tau \sim 0$ fm/c
$\tau \sim 1$ fm/c
$\tau \sim 10$ fm/c
$\tau \sim 10^{15}$ fm/c

Photon puzzle

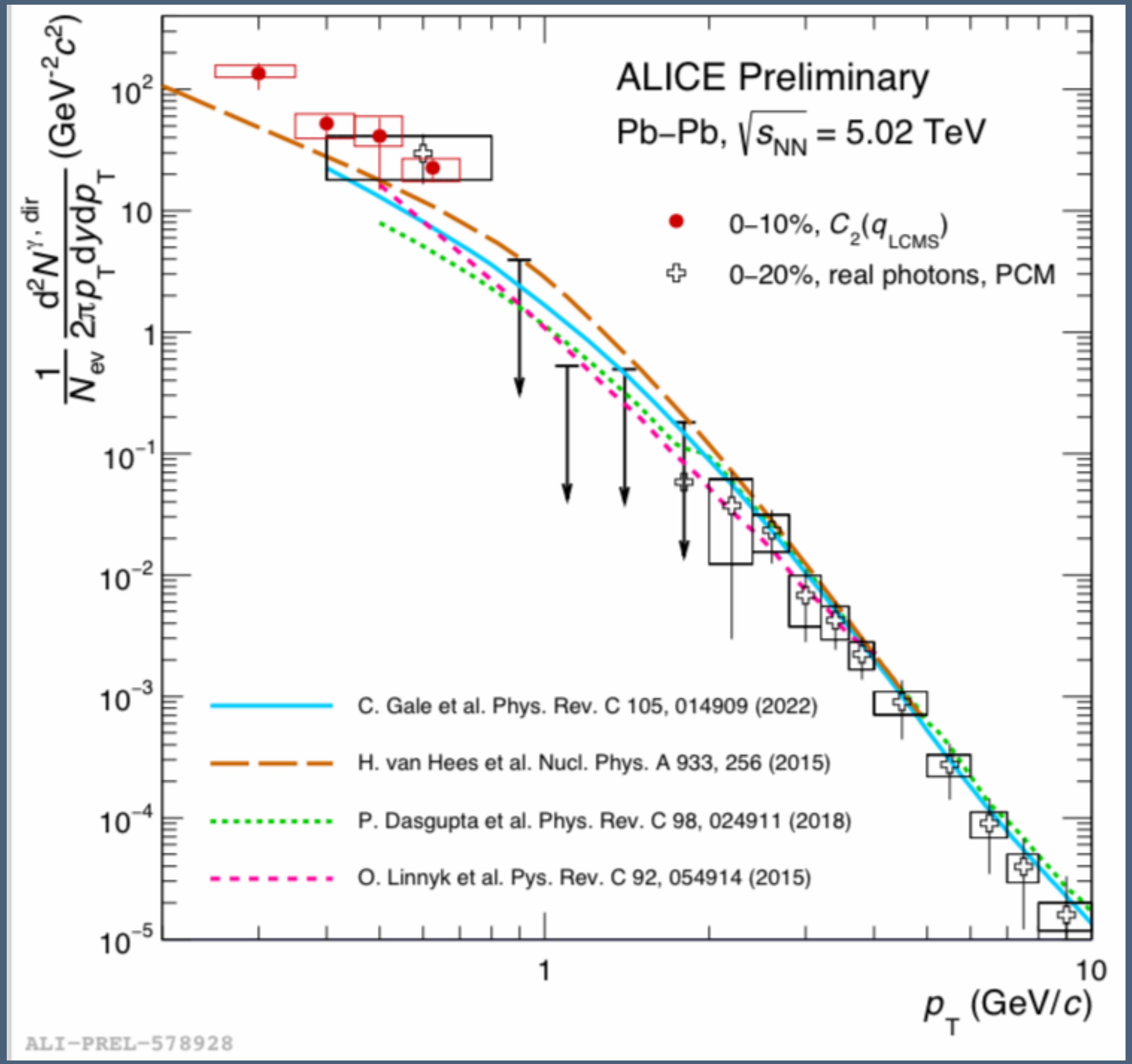


PRC **93**, 044906 (2016), arXiv:1509.06738

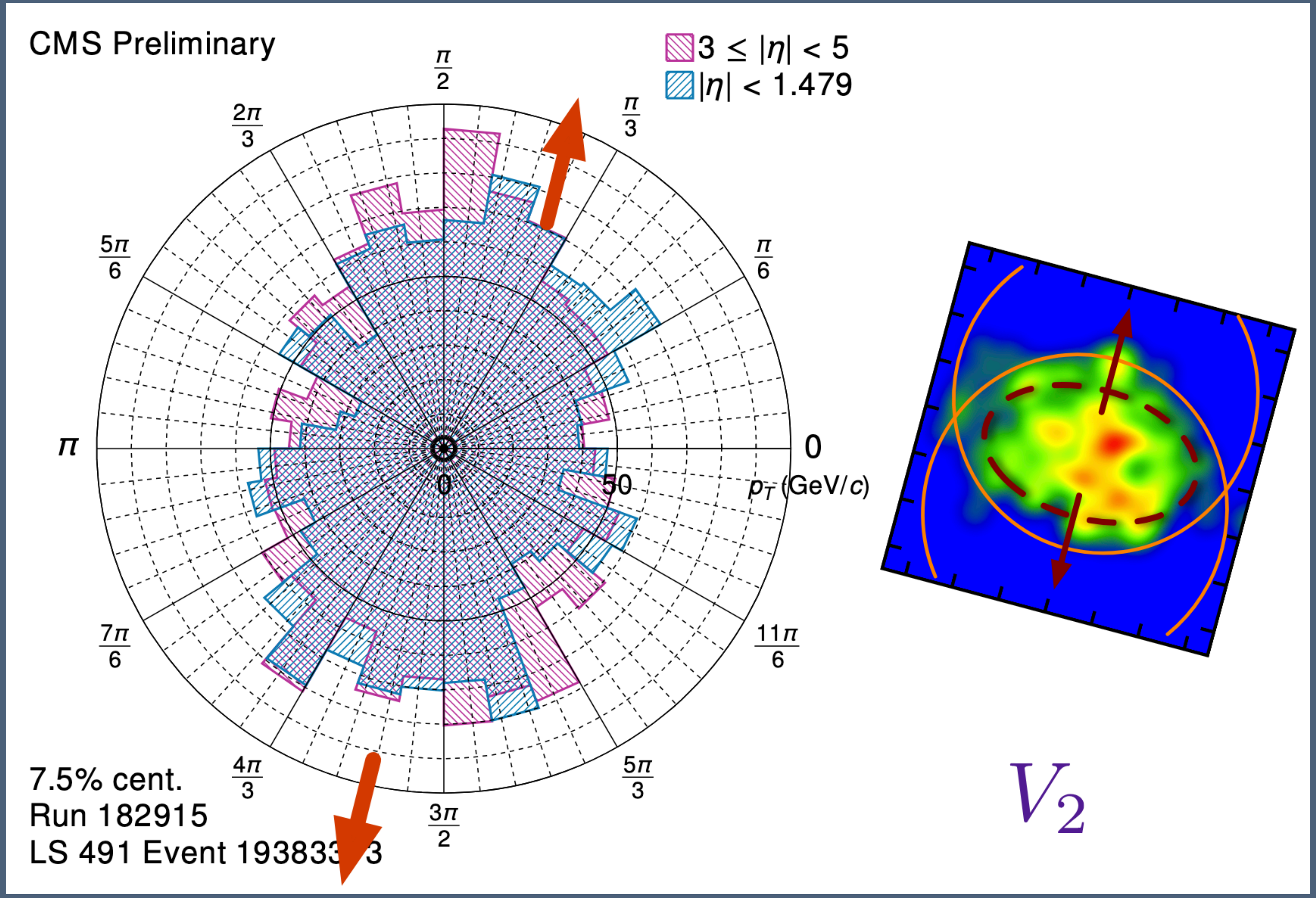


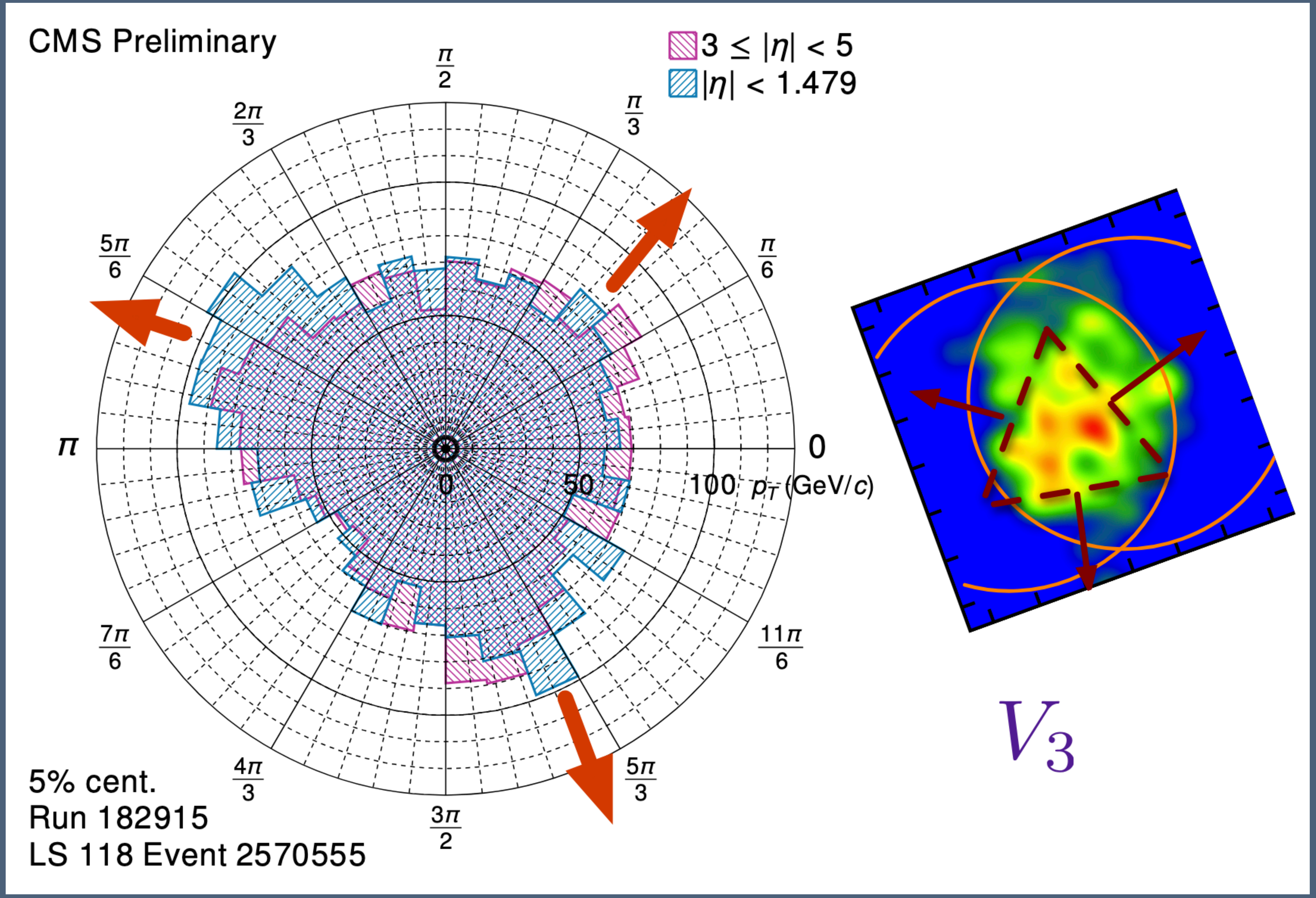
EPJ A **56**, 53 (2020), arXiv:1904.02938

Photon puzzle



Elliptic and triangular flow





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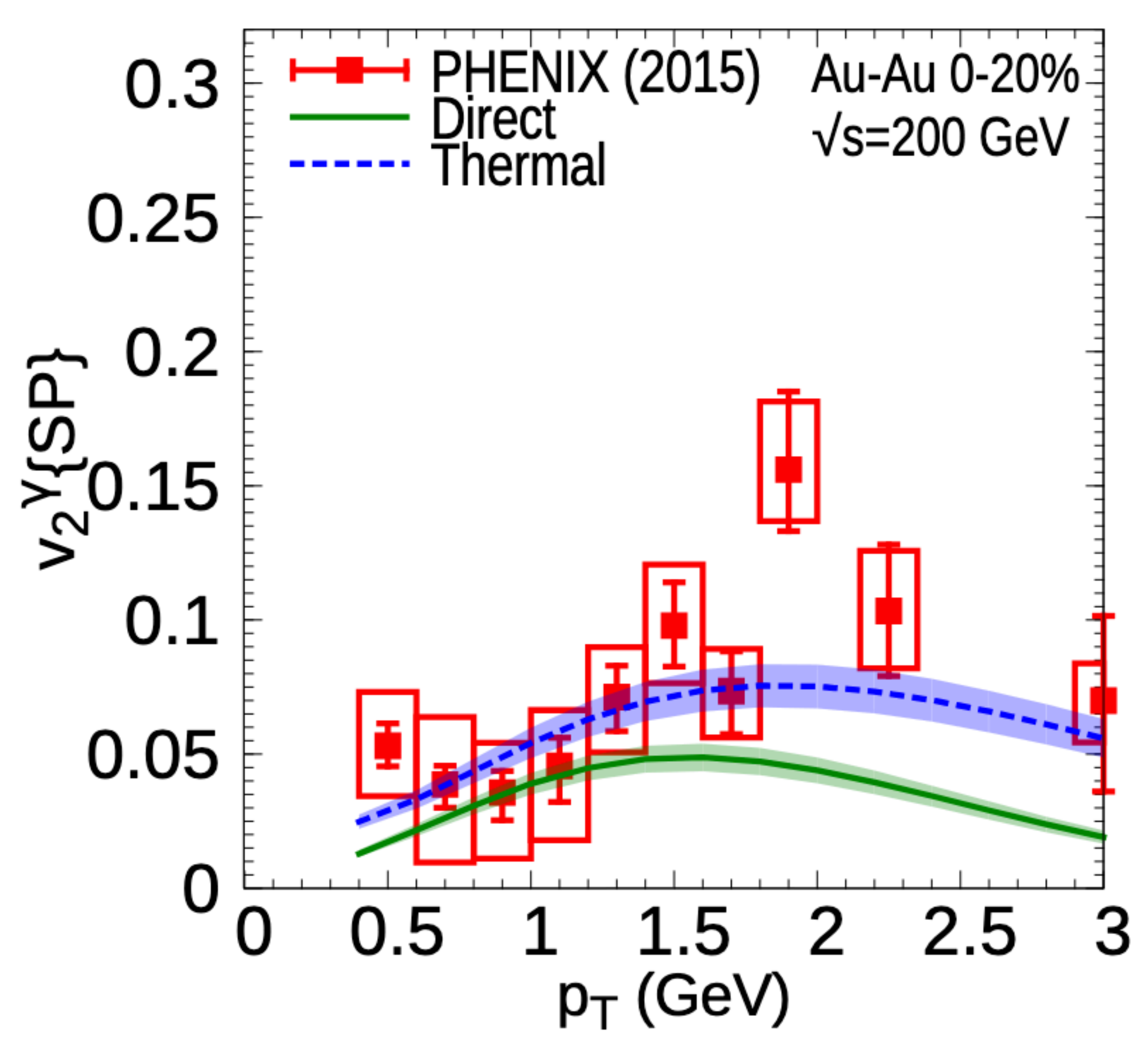
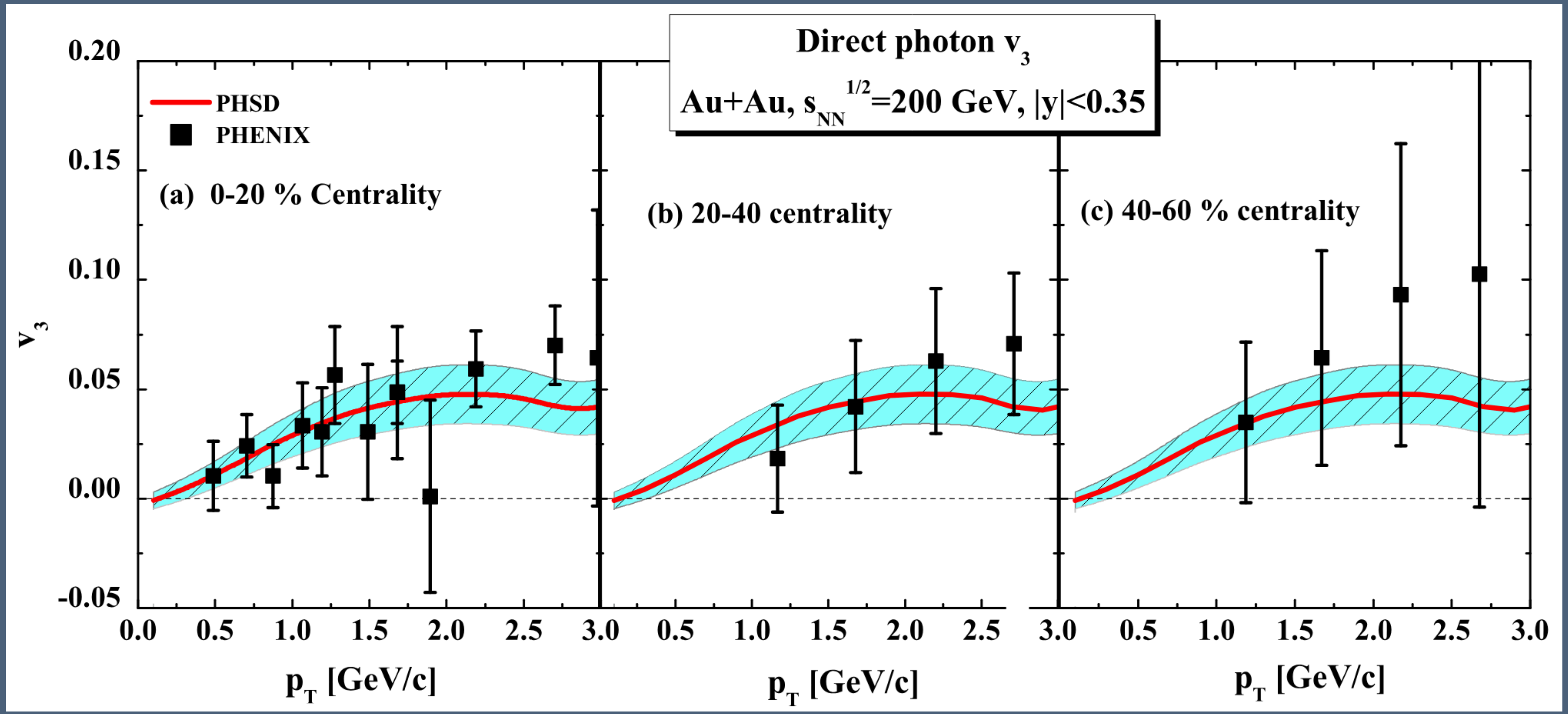
https://www.public.asu.edu/~ishovkov/colloquium/slides/Colloquium_Slides_Teaney.pdf

Photon puzzle

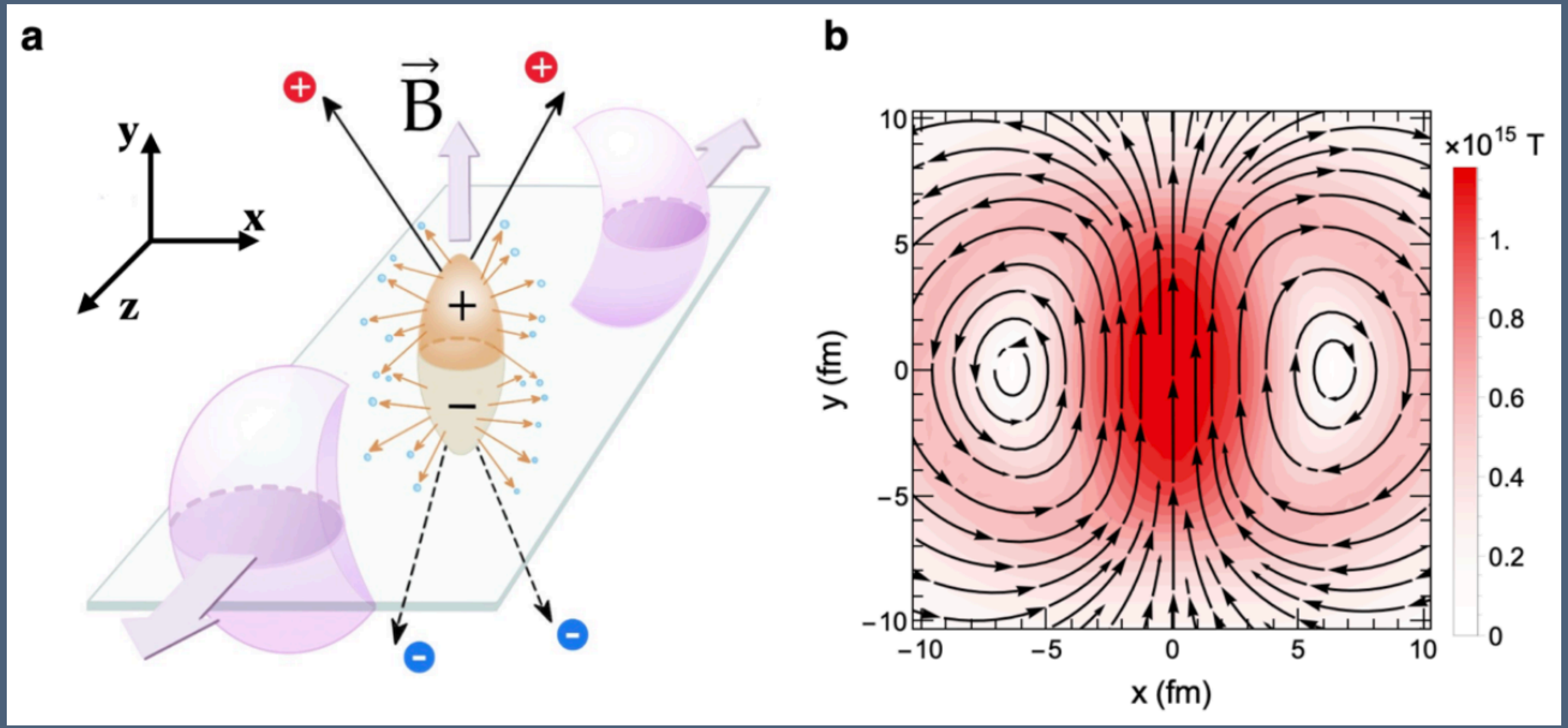


PRC **93**, 044906 (2016), arXiv:1509.06738

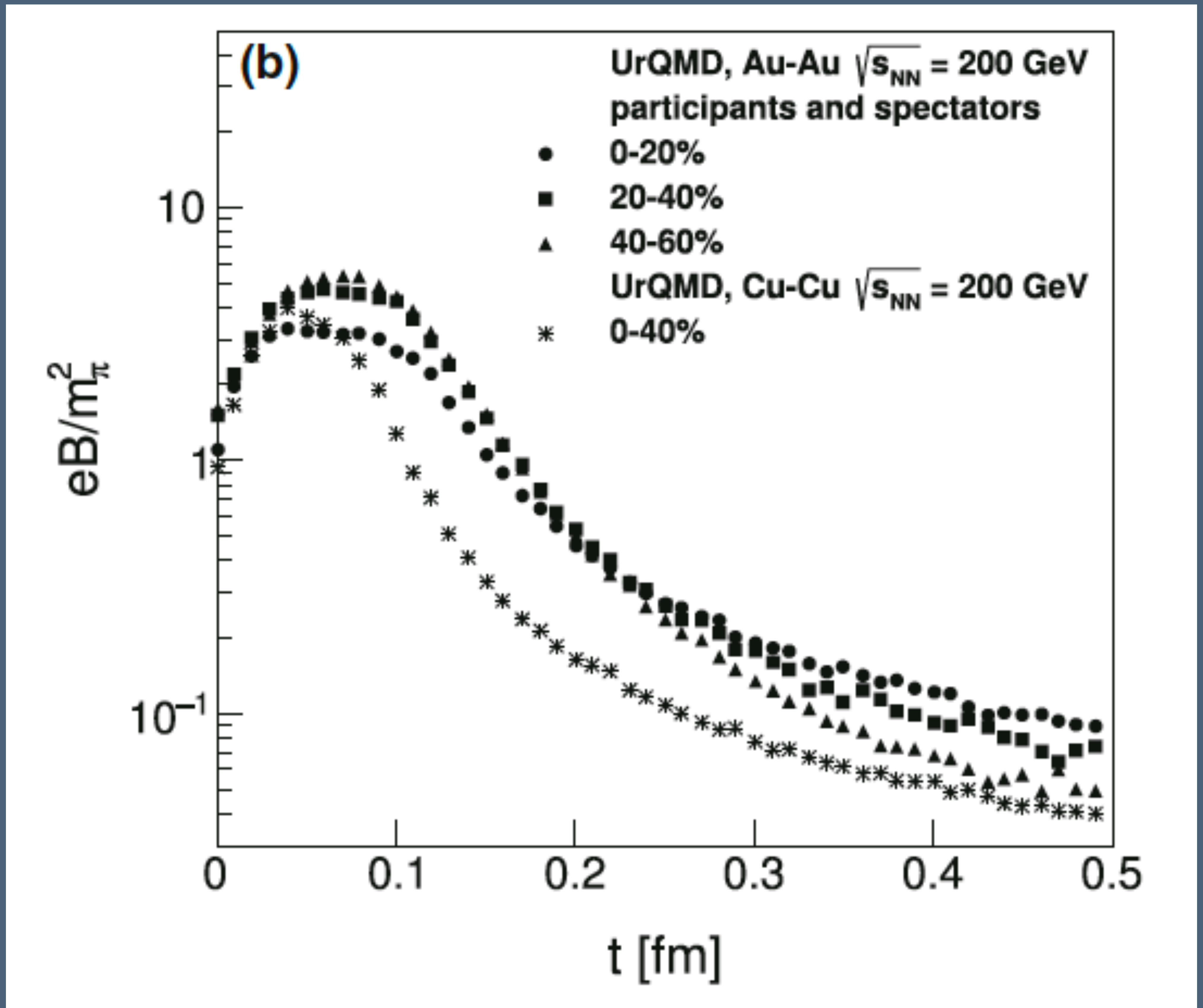


Prog. Part. Nucl. Phys. **87**, 50 (2016), arXiv:1512.08126

Magnetic fields



Nature Rev. Phys. **3**, 55 (2021), arXiv:2102.06623

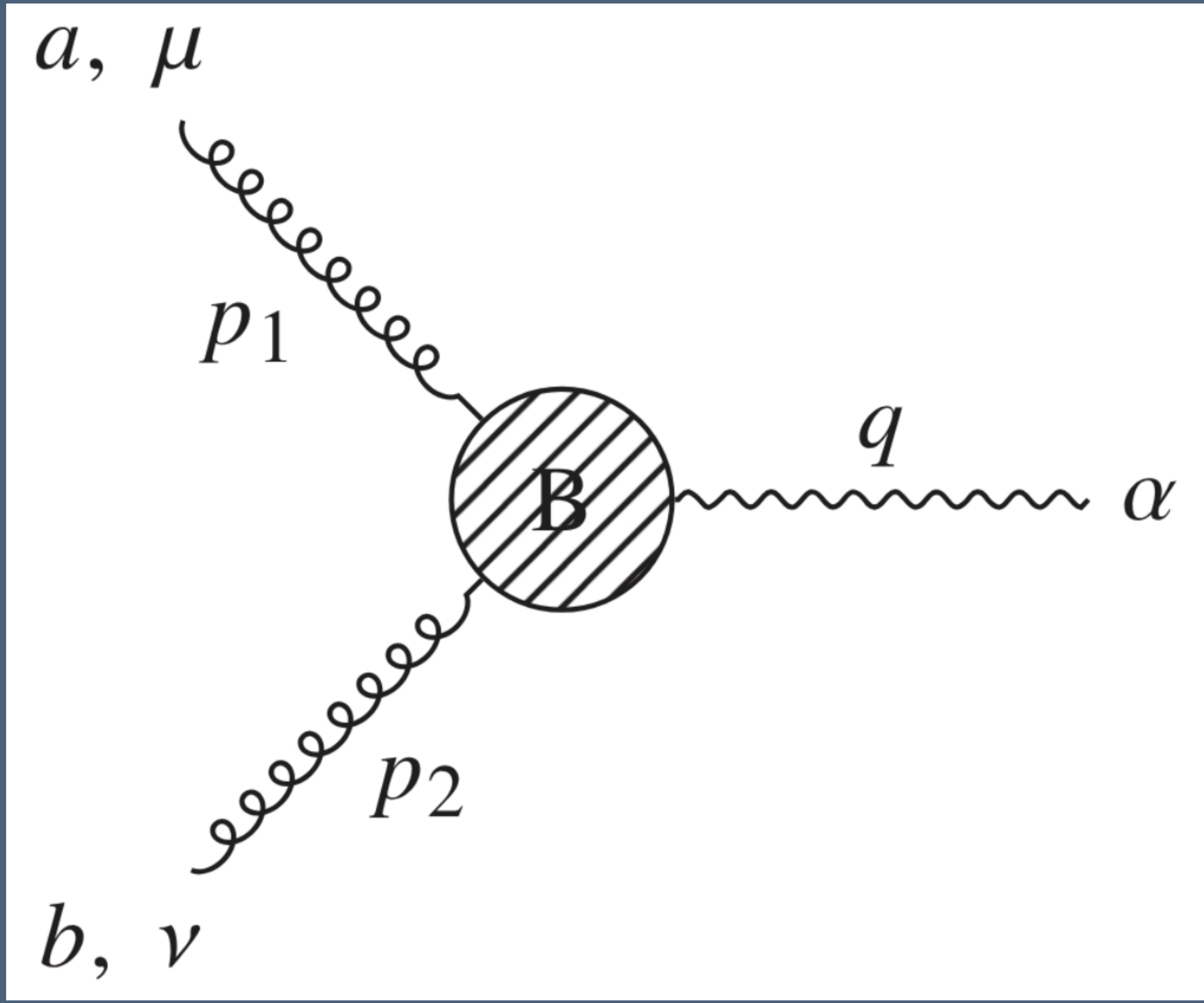


EPJ A **56**, 53 (2020), arXiv:1904.02938

Two-gluon one-photon vertex

General structure

- From gauge invariance, the vertex must be transverse when contracted with the gluons and photons momenta
- The vertex must be symmetric under gluon exchange
- The vertex is invariant under CP
- The basis will be expressed as a set of polarization vectors and the photon's momentum:
- q^μ
- $l_q^\mu \equiv \hat{F}^{\mu\beta} q_\beta$
- $l_q^{*\mu} \equiv \hat{F}^{*\mu\beta} q_\beta$
- $k_q^\mu \equiv \frac{q^2}{l_q^2} \hat{F}^{\mu\beta} \hat{F}_{\beta\sigma} q^\sigma + q^\mu$



Two-gluon one-photon vertex

General structure

- Assuming a constant magnetic field in the $\hat{z}$ direction, the polarizations can be explicitly written
- In principle, there are 27 possible tensor structures that can be constructed with q^μ, $\hat{l}_q^{*,\mu}$, $\hat{l}_q^{*,\mu}$ and k_q^μ
- By considering the gluon exchange symmetry, that number is reduced to 18
- Assuming that the gauge bosons are on-shell, then $k_q^\mu \to q^\mu$
- Imposing the conservation of energy-momentum, which implies that the gauge bosons are collinear

Two-gluon one-photon vertex

General structure

- If we write the transformation properties of each coefficient as a_i^{CP} and consider all the possible Lorentz scalars that can be constructed, it is possible to see that odd structures with respect to $\hat{C}$ and $\hat{P}$, are not available to express the on-shell vertex

- Hence we arrive at

- $\Gamma^{\mu\nu\alpha}_{ab}(p_1, p_2, q)_{\text{on-shell}} = a_1^{++}\hat{l}^{\mu}_{p_1\,a}\hat{l}^{\nu}_{p_2\,b}\hat{l}^{\alpha}_{q} + a_2^{++}\hat{l}^{*\mu}_{p_1\,a}\hat{l}^{*\nu}_{p_2\,b}\hat{l}^{\alpha}_{q} + \dfrac{a_{10}^{++}}{2}\,\hat{l}^{\mu}_{p_1\,a}\hat{l}^{*\nu}_{p_2\,b} + \hat{l}^{*\mu}_{p_1\,a}\hat{l}^{\nu}_{p_2\,b}\,\hat{l}^{*\alpha}_{q}$

Two-gluon one-photon vertex

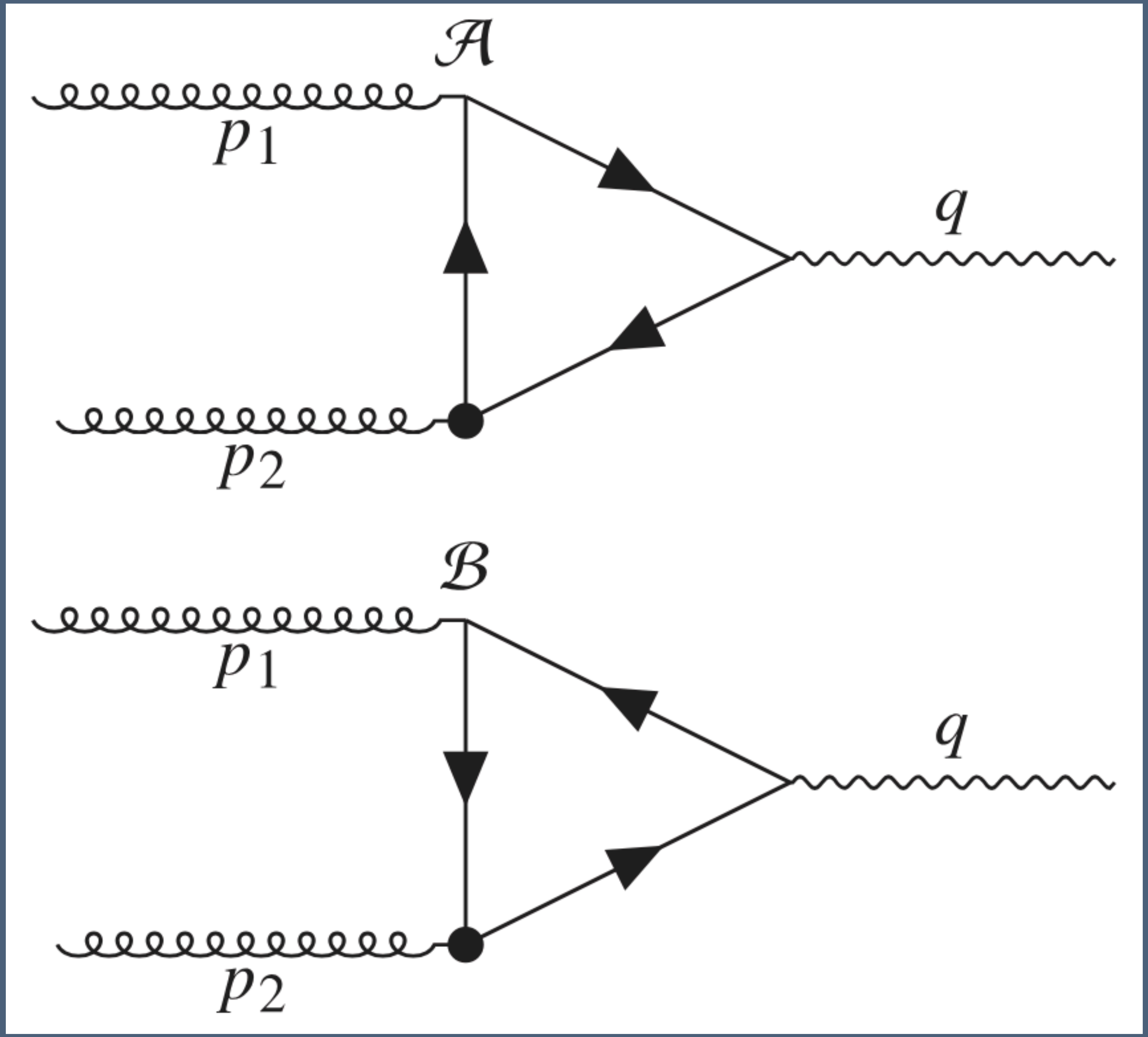
One-loop approximation

- At the leading order in α_s and α_{em}, the vertex is

- $$\Gamma^{\mu\nu\alpha}_{ab} = -ig^2 q_f \int d^4x d^4y d^4z \int \frac{d^4r_1}{(2\pi)^4}\frac{d^4r_2}{(2\pi)^4}\frac{d^4r_3}{(2\pi)^4}$$
$$\times\ e^{-ir_3\cdot(y-x)} e^{-ir_2\cdot(x-z)} e^{-ir_1\cdot(z-y)} e^{-ip_1\cdot z} e^{-ip_1\cdot z} e^{-ip_2\cdot y} e^{-ip_3\cdot x}$$
$$\times \mathrm{Tr}\, \gamma_\alpha S(r_2)\gamma_\mu t_a S(r_1)\gamma_\nu t_b S(r_3)\, \Phi(x,y,z,x)$$
$$\times \mathrm{Tr}\, \gamma_\alpha S(r_3)\gamma_\nu t_a S(r_1)\gamma_\mu t_b S(r_2)\, \Phi(x,z,y,x)$$

- Where $\Phi(x,y,z,x)$ is the product of Schiwnger phases and

- $$S(p) = \int_0^\infty \frac{ds}{\cos(q_f Bs)} e^{isp_\parallel^2 + p_\perp^2 \frac{\tan(q_f Bs)}{q_f Bs} - m_f^2 + i\epsilon}\, e^{iq_f Bs\Sigma_3}(m_f + \not{p}_\parallel) + \frac{\not{p}_\perp}{\cos(q_f Bs)}$$



Two-gluon one-photon vertex

One-loop approximation

- In the on-shell limit, the vertex is

$$\Gamma^{\mu\nu\alpha}_{ab} = -i\frac{g^2 q_f^2 B}{2\pi^2}\mathrm{Tr}[t_a t_b]\delta^4(p_1+p_2-q)$$

$$\times \int_0^\infty \frac{ds_1 ds_2 ds_3}{c_1^2 c_2^2 c_3^2}\frac{1}{t_1t_2t_3 - t_1 - t_2 - t_3}\frac{e^{-ism_f^2}}{s}$$

$$\times\ e^{-\frac{i}{s}(s_1s_3\omega_{p_1}^2 + s_2s_3\omega_{p_2}^2 + s_1s_2\omega_q^2)\frac{q_\perp^2}{\omega_q^2}}$$

$$\times\ e^{-\frac{i}{\omega_q^2}\frac{q_\perp^2}{|q_fB|}\frac{1}{t_1t_2t_3-t_1-t_2-t_3}(t_1t_3\omega_{p_1}^2 + t_2t_3\omega_{p_2}^2 + t_1t_2\omega_q^2)}$$

$$\times \sum_{j=1}^{19} T^{\mu\nu\alpha}_{\mathcal{A}_j} + T^{\mu\nu\alpha}_{\mathcal{B}_j}$$

$$T^{\mu\nu\alpha}_{\mathcal{A}1} + T^{\mu\nu\alpha}_{\mathcal{B}1} = \mathrm{Tr}[\gamma^\mu \not{\mathcal{A}}_a \gamma^\alpha \not{\mathcal{A}}_b \gamma^\nu \not{\mathcal{A}}_c] + \mathrm{Tr}[\gamma^\mu \not{\mathcal{B}}_c \gamma^\nu \not{\mathcal{B}}_b \gamma^\alpha \not{\mathcal{B}}_a],$$

$$T^{\mu\nu\alpha}_{\mathcal{A}2} + T^{\mu\nu\alpha}_{\mathcal{B}2} = m_f^2\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha e_2 \gamma^\nu \not{\mathcal{A}}_c] + \mathrm{Tr}[\gamma^\mu \not{\mathcal{B}}_c \gamma^\nu e_2 \gamma^\alpha e_1]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}3} + T^{\mu\nu\alpha}_{\mathcal{B}3} = m_f^2\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha \not{\mathcal{A}}_b \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu \not{\mathcal{B}}_b \gamma^\alpha e_1]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}4} + T^{\mu\nu\alpha}_{\mathcal{B}4} = m_f^2\{\mathrm{Tr}[\gamma^\mu \not{\mathcal{A}}_a \gamma^\alpha e_2 \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu e_2 \gamma^\alpha \not{\mathcal{B}}_a]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}5} + T^{\mu\nu\alpha}_{\mathcal{B}5} = \frac{i}{s}\{\mathrm{Tr}[\gamma^\mu \not{\mathcal{A}}_a \gamma^\alpha e_2 \gamma^\nu_\parallel e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu_\parallel e_2 \gamma^\alpha \not{\mathcal{B}}_a]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}6} + T^{\mu\nu\alpha}_{\mathcal{B}6} = \frac{i}{s}\{\mathrm{Tr}[\gamma^\mu_\parallel e_1 \gamma^\alpha \not{\mathcal{A}}_b \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu_\parallel e_3 \gamma^\nu \not{\mathcal{B}}_b \gamma^\alpha e_1]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}7} + T^{\mu\nu\alpha}_{\mathcal{B}7} = \frac{i}{s}\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha_\parallel e_2 \gamma^\nu \not{\mathcal{A}}_c] + \mathrm{Tr}[\gamma^\mu \not{\mathcal{B}}_c \gamma^\nu e_2 \gamma^\alpha_\parallel e_1]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}8} + T^{\mu\nu\alpha}_{\mathcal{B}8} = -\frac{i}{s}\{\mathrm{Tr}[\gamma^\mu \not{\mathcal{A}}_a \gamma^\alpha e_2 \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu e_2 \gamma^\alpha \not{\mathcal{B}}_a]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}9} + T^{\mu\nu\alpha}_{\mathcal{B}9} = -\frac{i}{s}\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha \not{\mathcal{A}}_b \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu \not{\mathcal{B}}_b \gamma^\alpha e_1]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}10} + T^{\mu\nu\alpha}_{\mathcal{B}10} = -\frac{i}{s}\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha e_2 \gamma^\nu \not{\mathcal{A}}_c] + \mathrm{Tr}[\gamma^\mu \not{\mathcal{B}}_c \gamma^\nu e_2 \gamma^\alpha e_1]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}11} + T^{\mu\nu\alpha}_{\mathcal{B}11} = \frac{iq_fB}{(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \not{\mathcal{A}}_a \gamma^\alpha \gamma^\nu] + \mathrm{Tr}[\gamma^\mu \gamma^\nu \gamma^\alpha \not{\mathcal{B}}_a]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}12} + T^{\mu\nu\alpha}_{\mathcal{B}12} = \frac{iq_fB}{(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\alpha \not{\mathcal{A}}_b \gamma^\nu] + \mathrm{Tr}[\gamma^\mu \gamma^\nu \not{\mathcal{B}}_b \gamma^\alpha]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}13} + T^{\mu\nu\alpha}_{\mathcal{B}13} = \frac{iq_fB}{(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\alpha \gamma^\nu \not{\mathcal{A}}_c] + \mathrm{Tr}[\gamma^\mu \not{\mathcal{B}}_c \gamma^\nu \gamma^\alpha]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}14} + T^{\mu\nu\alpha}_{\mathcal{B}14} = -\frac{iq_fB}{(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \not{\mathcal{A}}_a \gamma^\alpha \gamma^\nu_\perp] + \mathrm{Tr}[\gamma^\mu \gamma^\nu_\perp \gamma^\alpha \not{\mathcal{B}}_a]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}15} + T^{\mu\nu\alpha}_{\mathcal{B}15} = -\frac{iq_fB}{(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu_\perp \gamma^\alpha \not{\mathcal{A}}_b \gamma^\nu] + \mathrm{Tr}[\gamma^\mu_\perp \gamma^\nu \not{\mathcal{B}}_b \gamma^\alpha]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}16} + T^{\mu\nu\alpha}_{\mathcal{B}16} = -\frac{iq_fB}{(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\alpha_\perp \gamma^\nu \not{\mathcal{A}}_c] + \mathrm{Tr}[\gamma^\mu \not{\mathcal{B}}_c \gamma^\nu \gamma^\alpha_\perp]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}17} + T^{\mu\nu\alpha}_{\mathcal{B}17} = \frac{iq_fBt_1}{2(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \not{\mathcal{A}}_a \gamma^\alpha \gamma^\beta_\perp \gamma^\nu \gamma^\sigma_\perp]\hat{F}_{\beta\sigma} + \mathrm{Tr}[\gamma^\mu \gamma^\sigma_\perp \gamma^\nu \gamma^\beta_\perp \gamma^\alpha \not{\mathcal{B}}_a]\hat{F}_{\sigma\beta}\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}18} + T^{\mu\nu\alpha}_{\mathcal{B}18} = -\frac{iq_fBt_2}{2(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\beta_\perp \gamma^\alpha \not{\mathcal{A}}_b \gamma^\nu \gamma^\sigma_\perp]\hat{F}_{\beta\sigma} + \mathrm{Tr}[\gamma^\mu \gamma^\sigma_\perp \gamma^\nu \not{\mathcal{B}}_b \gamma^\alpha \gamma^\beta_\perp]\hat{F}_{\sigma\beta}\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}19} + T^{\mu\nu\alpha}_{\mathcal{B}19} = \frac{iq_fBt_3}{2(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\beta_\perp \gamma^\alpha \gamma^\sigma_\perp \gamma^\nu \not{\mathcal{A}}_c]\hat{F}_{\beta\sigma} + \mathrm{Tr}[\gamma^\mu \not{\mathcal{B}}_c \gamma^\nu \gamma^\sigma_\perp \gamma^\alpha \gamma^\beta_\perp]\hat{F}_{\sigma\beta}\},$$

$$\not{\mathcal{A}}_a = -\left(\frac{s_3\omega_{p_1} + s_2\omega_q}{s\omega_q}\right)\not{q}_\parallel e_1 + \frac{(t_3\omega_{p_1} + t_2\omega_q)\not{q}_\perp - t_2t_3\omega_{p_2}\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{(t_1t_2t_3 - t_1 - t_2 - t_3)\omega_q}$$

$$\not{\mathcal{A}}_b = \left(\frac{s_1\omega_q + s_3\omega_{p_2}}{s\omega_q}\right)\not{q}_\parallel e_2 - \frac{(t_3\omega_{p_2} + t_1\omega_q)\not{q}_\perp + t_1t_3\omega_{p_1}\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{(t_1t_2t_3 - t_1 - t_2 - t_3)\omega_q}$$

$$\not{\mathcal{A}}_c = \left(\frac{s_1\omega_{p_1} - s_2\omega_{p_2}}{s\omega_q}\right)\not{q}_\parallel e_3 + \frac{(-t_1\omega_{p_1} + t_2\omega_{p_2})\not{q}_\perp + t_1t_3\omega_q\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{(t_1t_2t_3 - t_1 - t_2 - t_3)\omega_q}$$

$$\not{\mathcal{B}}_a = \left(\frac{s_3\omega_{p_1} + s_2\omega_q}{s\omega_q}\right)\not{q}_\parallel e_1 - \frac{(t_3\omega_{p_1} + t_2\omega_q)\not{q}_\perp + t_2t_3\omega_{p_2}\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{(t_1t_2t_3 - t_1 - t_2 - t_3)\omega_q}$$

$$\not{\mathcal{B}}_b = -\left(\frac{s_1\omega_q + s_3\omega_{p_2}}{s\omega_q}\right)\not{q}_\parallel e_2 + \frac{(t_3\omega_{p_2} + t_1\omega_q)\not{q}_\perp - t_1t_3\omega_{p_1}\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{(t_1t_2t_3 - t_1 - t_2 - t_3)\omega_q}$$

$$\not{\mathcal{B}}_c = -\left(\frac{s_1\omega_{p_1} - s_2\omega_{p_2}}{s\omega_q}\right)\not{q}_\parallel e_3 + \frac{(t_1\omega_{p_1} - t_2\omega_{p_2})\not{q}_\perp + t_1t_3\omega_q\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{(t_1t_2t_3 - t_1 - t_2 - t_3)\omega_q}.$$

Two-gluon one-photon vertex

One-loop approximation at the intermediate field regime

- Since we are interested in the regime where $q_f B \sim m_\pi^2$ and $q_\perp \gtrsim 500$ MeV, the hierarchy of scales is $m_f^2 < |q_f B| < q_\perp^2$

- If we perform the change of variable $s_i = s v_i$ with $v_3 = 1 - v_1 - v_2$, $v_1 \leq 1$ and $v_2 \leq 1 - v_1$, in general we have integrals of the form

- $\sum_{j=1}^{19} \int ds\, dv_1\, dv_2\, \csc^{i+1}(x)\, e^{i\text{Arg}}\, G_j^{\mu\nu\alpha}$, where $i = 1,2,3$, $\text{Arg} = \dfrac{q_\perp^2}{|q_f B|} x^3 F(v_1, v_2)$ and
$G_j^{\mu\nu\alpha} = i\dfrac{g^2 q_f}{16\pi^2}\text{Tr}[t_a t_b] x \sec(v_1 x)\sec(v_2 x)\sec(x(1 - v_1 - v_2)) T_{\mathscr{A}_j}^{\mu\nu\alpha} + T_{\mathscr{B}_j}^{\mu\nu\alpha}$, with $s = x / q_f B$

- Where the region of the integrand that provides the largest contribution to the integral comes from $q_f B s \ll 1$, thus, we have neglected terms proportional to m_f^2

Two-gluon one-photon vertex

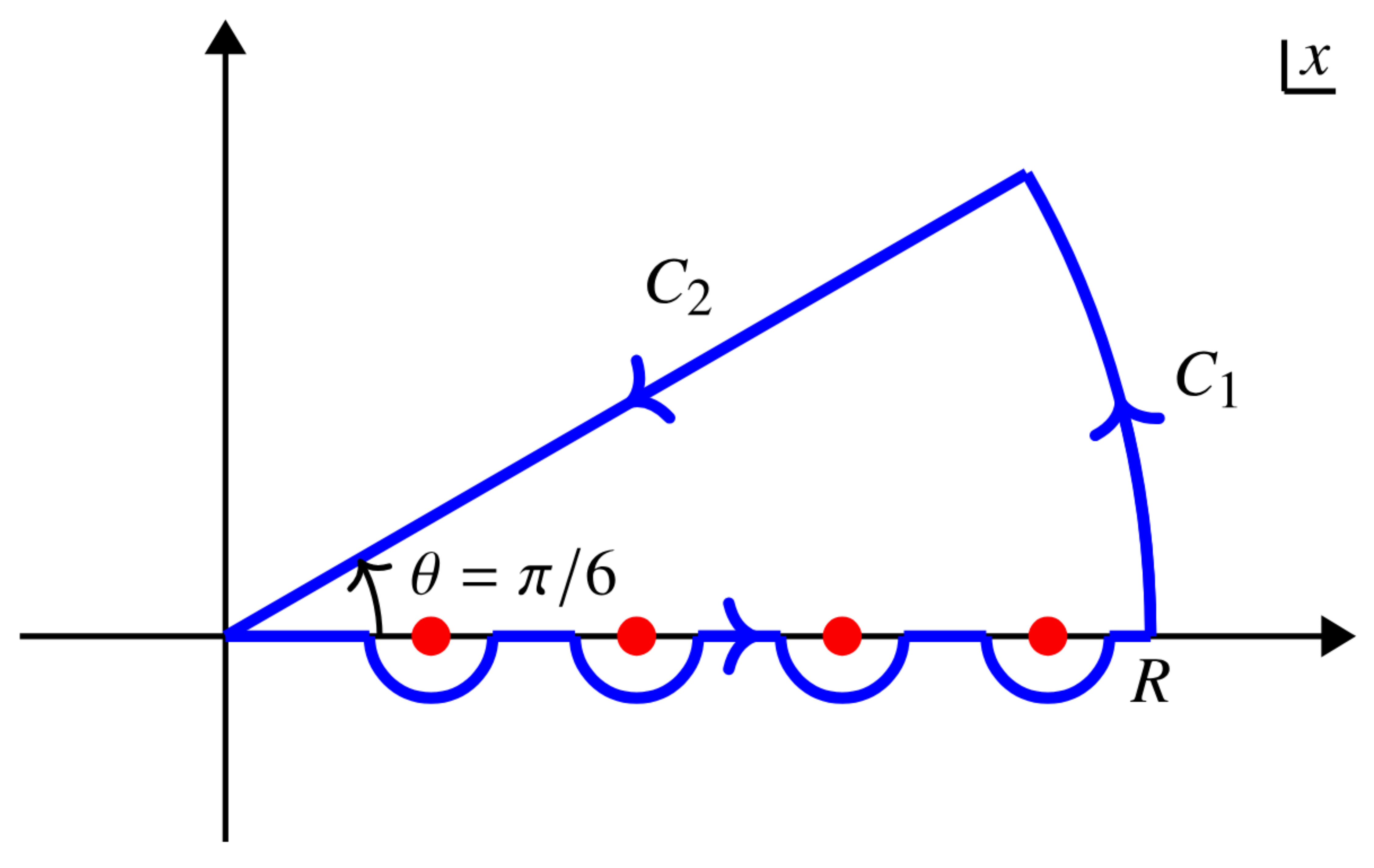
One-loop approximation at the intermediate field regime

- There are 3 kinds of integrands, all proportional to $\csc^i(x)$, with $i = 2, 3, 4$ and the principal value can be obtained as

- $$\int_0^\infty dx \csc^{j+1} e^{i\mathrm{Arg}} G_j(x, v_1, v_2) = \sum \mathrm{Res}(\csc^{j+1}(x) e^{i\mathrm{Arg}} G_j(x, v_1, v_2), n\pi) - \int_0^\infty d\tau \csc^{j+1}(\tau e^{i\pi/6}) e^{-\frac{q_\perp^2}{q_f B}\tau^3 F(v_1,v_2)} G_j(\tau e^{i\pi/6}, v_1, v_2)$$

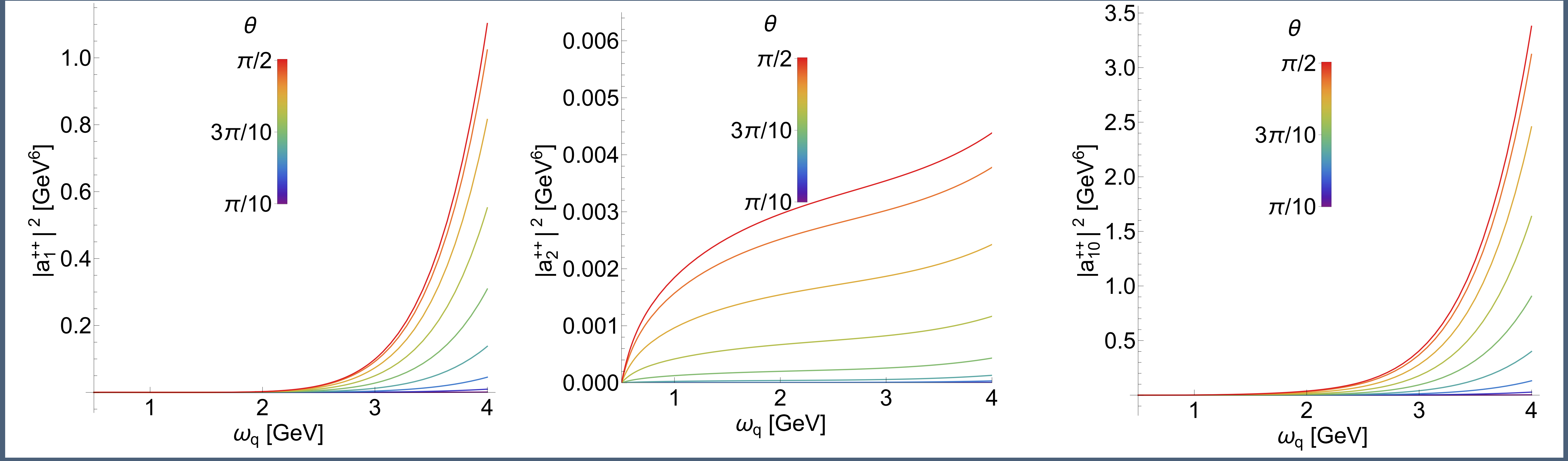
- To perform the integrals over v_1 and v_2 we resort to the stationary phase approximation

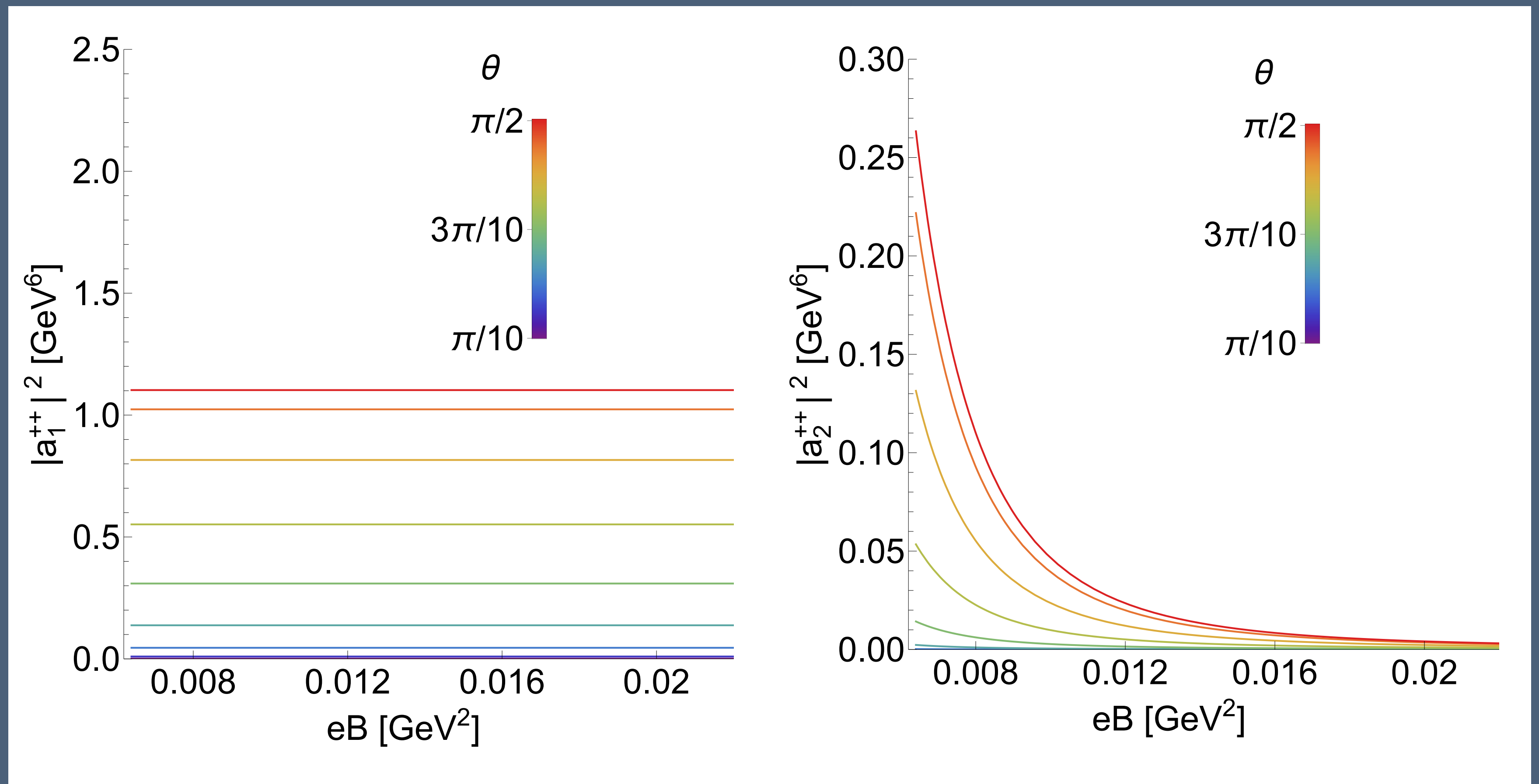
- $$\int dv_1 dv_2 \mathscr{F}(v_1, v_2) e^{i\chi\psi(v_1,v_2)} \approx \sum_{\vec{v}^0 \in \Upsilon} e^{i\chi\psi(\vec{v}^0} \,|\det(\mathrm{Hess}(\Psi(\vec{v}^0)))\,|^{1/2} \times e^{i\frac{\pi}{4}\mathrm{sign}(\mathrm{Hess}(\Psi(\vec{v}^0)))} \frac{2\pi}{\chi}^{2/2} \mathscr{F}(\vec{v}^0) + \mathcal{O}(\chi^{-1/2})$$

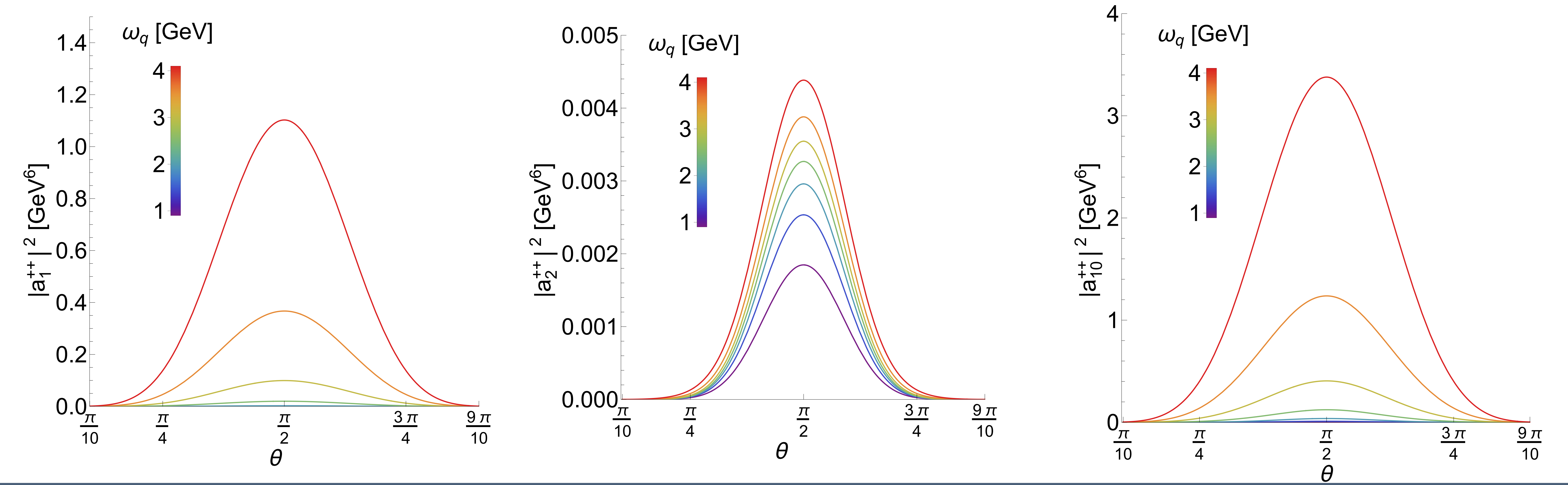


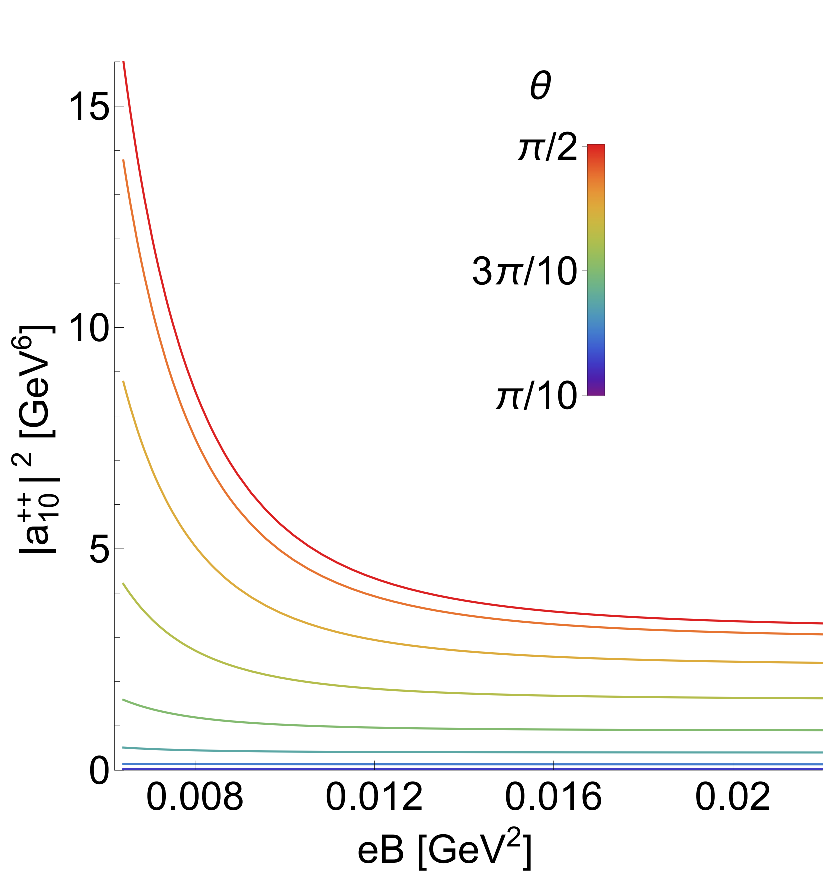
Two-gluon one-photon vertex

One-loop approximation at the intermediate field regime



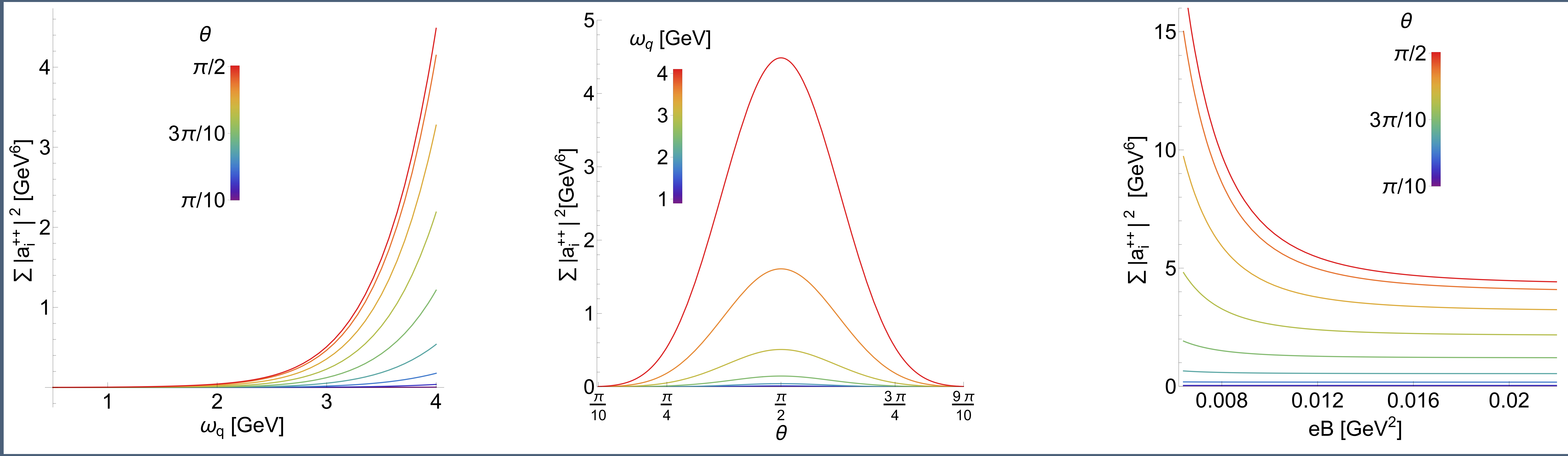






Two-gluon one-photon vertex

One-loop approximation at the intermediate field regime



Summary and conclusions

- We found the general structure of the two-gluon one-photon vertex in the presence of a constant magnetic field
- We have obtained it at the one-loop level in the intermediate field regime, which is the most appropriate one to describe the possible effects of the presence of a magnetic field as a catalyzer of photon emission during preequilibrium
- The most favored direction of photon propagation is transverse to the magnetic field (contribution to positive elliptic flow)
- These findings will be used for the computation of the photon yield and elliptic flow coefficient

Thank you !