Jet fragmentation photons in ultrarelativistic heavy-ion collisions

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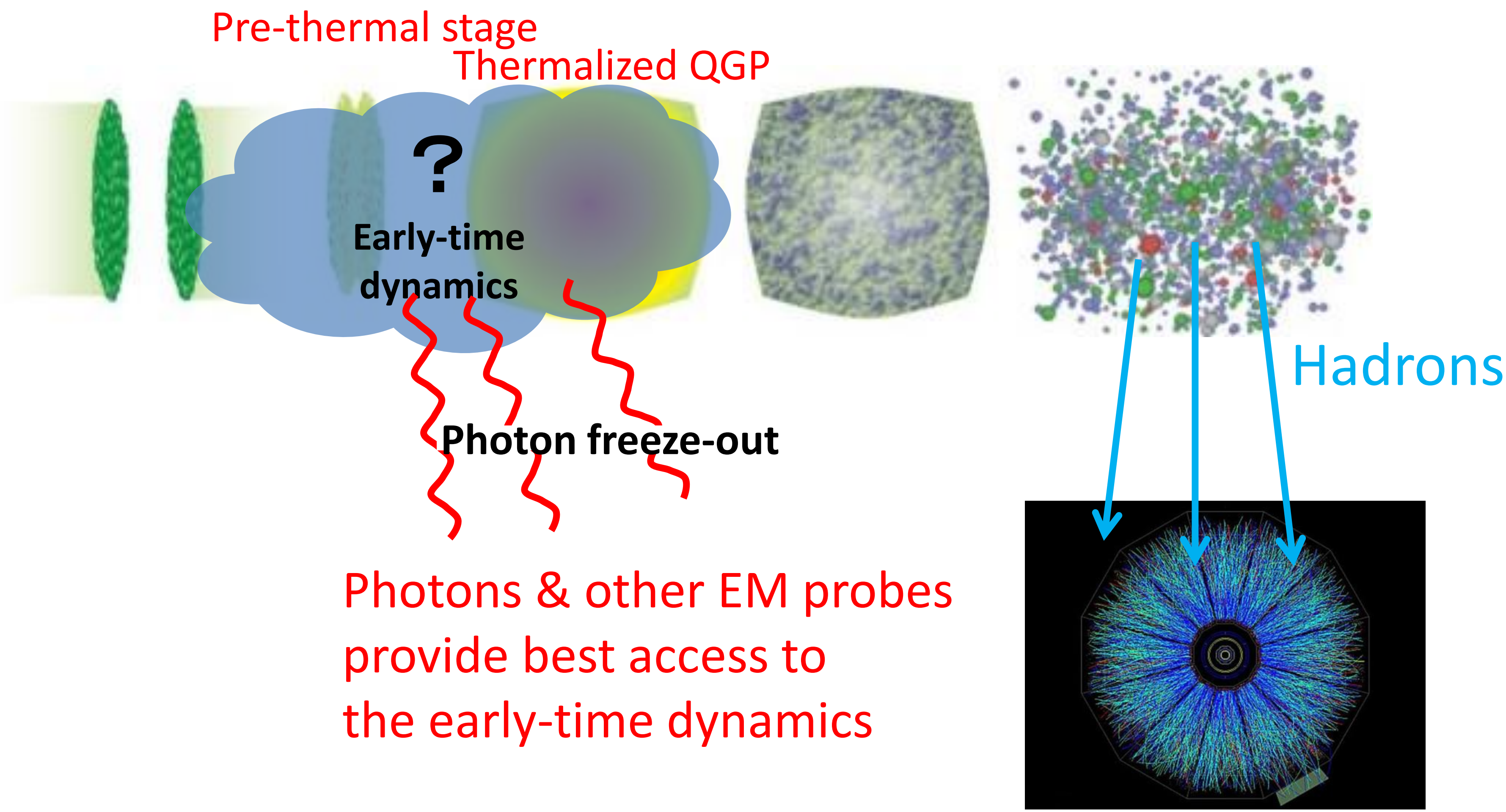
EM probes as messengers of early-time dynamics



Photons & other EM probes
provide best access to
the early-time dynamics

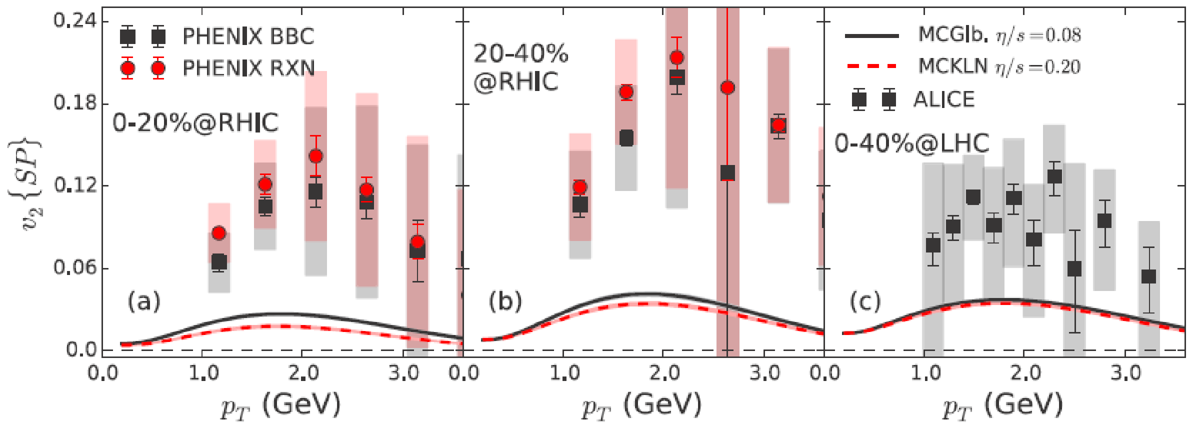
Shuryak (1978), McLerran & Toimela (1985), etc

Photon yield, v2, and v3 measured in RHIC and LHC!!

See next talks.

Recent theoretical progresses

Still small v2 in 2015 (Shen, et al., 2015.)



+ Bulk viscosity, etc. (J.-F.Paquet, et al. See his talk.)
+ NLO HTL photon rate (Ghiglieri, et al.)
+ Nonperturbative background in semi-QGP (BNL)
+ B-field (Basar, et al., Tuchin, HK, Itakura, etc.)
+ ……

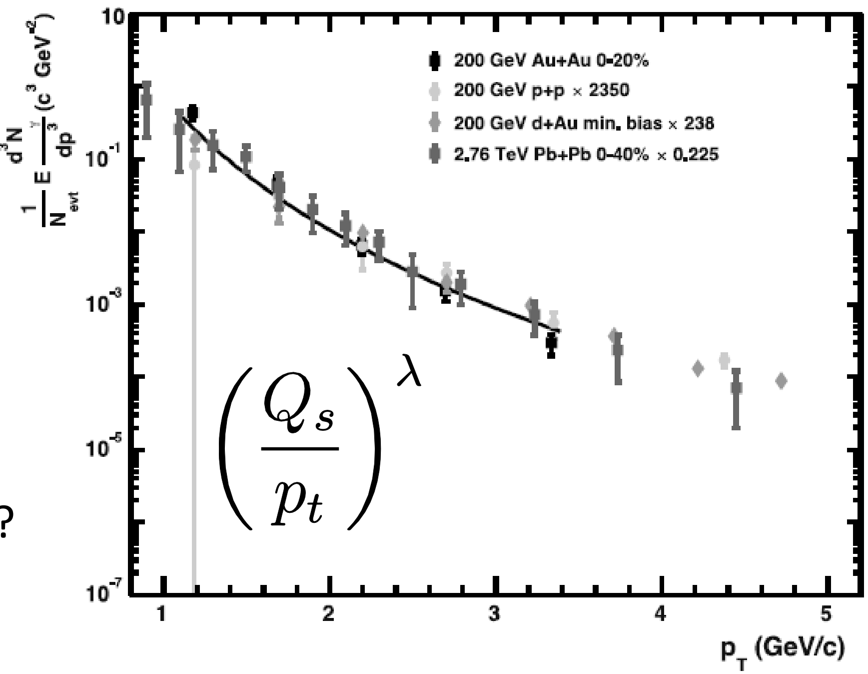
Geometrical scaling of photons
in pp, dA, AA @ RHIC & LHC

Suggests an early-time emission?

→ How is the information of Qs transferred to γ?

→ Is the large v2 again puzzling?

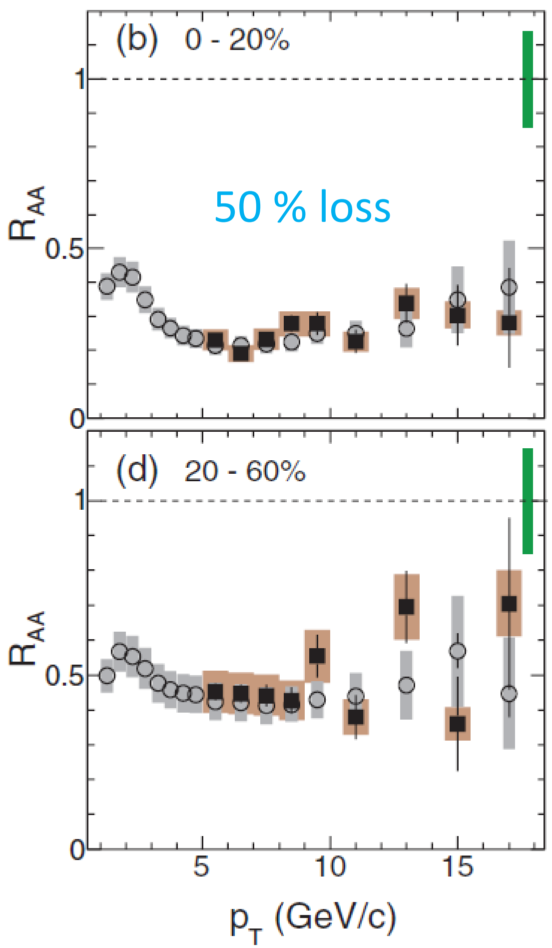
+ Glasma? (McLerran, Schenke; Tanji)
+ Jet fragmentation? → This talk



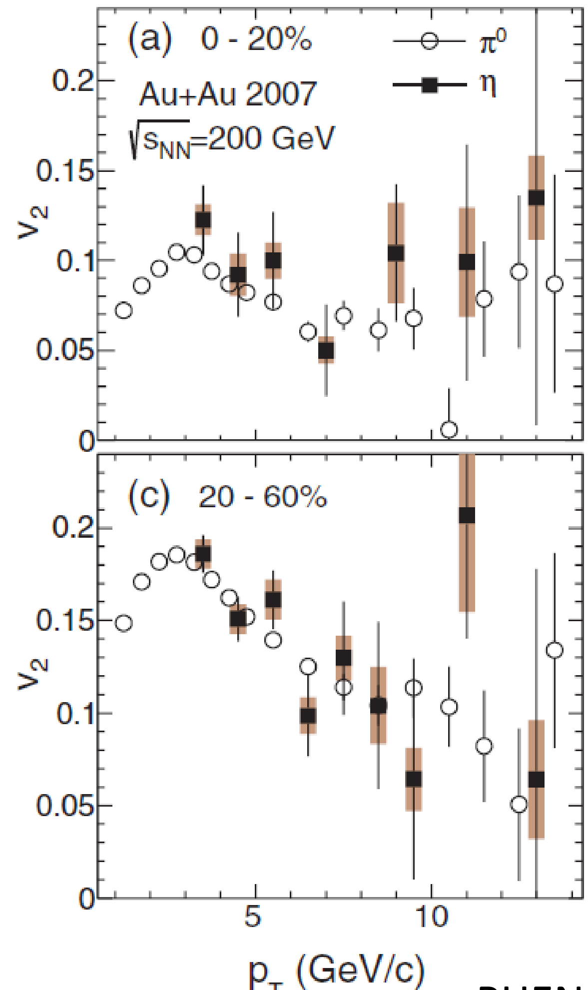
Klein-Boesing, McLerran (2014)

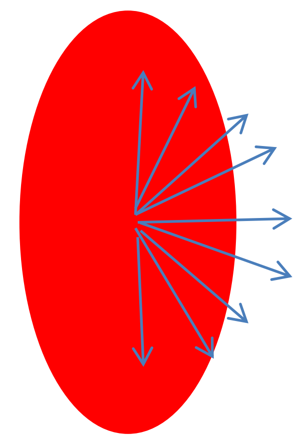
v_2 of jets generated by energy loss → Can be transferred to photon v2 ?

R_{AA} of high-p_t pi0



v2 of pi0 and eta at high p_t
-- Almost species independent





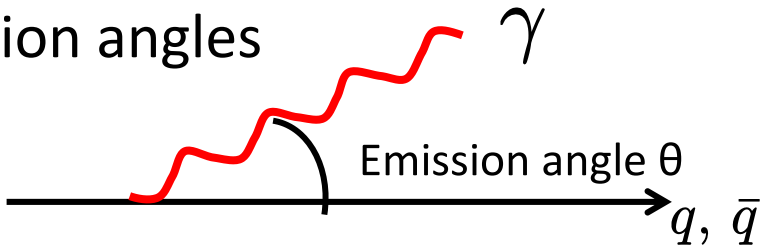
QGP eating jets

PHENIX, 2010, 2013

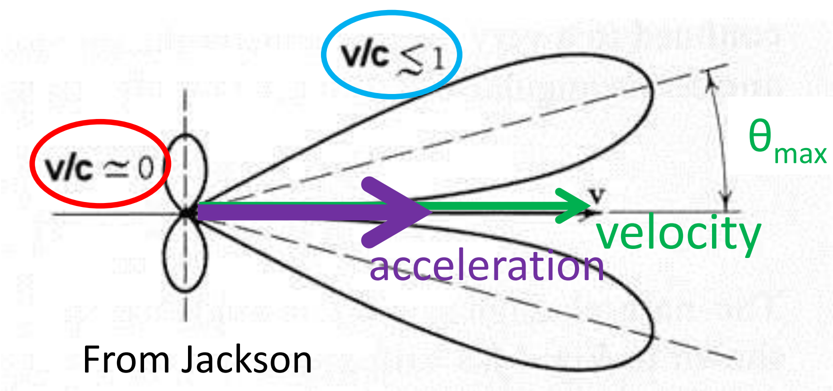
Estimates by classical electrodynamics

Provides a good approximation when kinematics is properly treated.

Velocity-dependence of emission angles



Bremsstrahlung from relativistic and nonrelativistic particles



Radiation in the linear acceleration

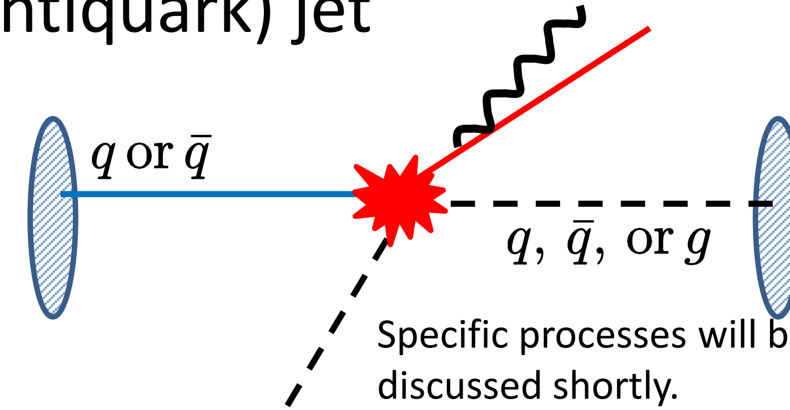
$$\boxed{\theta \to \frac{1}{2\gamma}\ \mathrm{as}\ v \to 1}$$

+ Relativistic particles
  Forward-dominant emission
  → Collimation btw the jet & photon momenta.

+ Non-relativistic particles
  Isotropic emission from
  → Uncollimated emission

c.f. "Dead-cone effect" in the heavy-quark jet energy loss, Dokshitzer, Kharzeev (2001)

Bremsstrahlung from a quark (antiquark) jet



Specific processes will be discussed shortly.

Photon emission rate from quark current

$$2\epsilon_{\boldsymbol{p}} \frac{dn_\gamma}{d^3\boldsymbol{p}} = -\frac{1}{(2\pi)^3}\, \tilde{j}^\mu(p)\tilde{j}^*_\mu(p)\Big|_{p^0=|\boldsymbol{p}|}$$

Quark (antiquark) current

$$j^\mu(x) = e\{\, v^\mu_{\text{ini}}\delta^{(3)}(\boldsymbol{x} - \boldsymbol{v}_{\text{ini}}t)\theta(-t) + v^\mu_{\text{fin}}\delta^{(3)}(\boldsymbol{x} - \boldsymbol{v}_{\text{fin}}t)\theta(t)\,\}$$

Classical trajectory after the scattering

Before the scattering $\qquad v_{\text{ini}} = (0, 0, 1)$

After the scattering $\qquad$ Finite jet mass $\qquad \epsilon^2_{\text{jet}} - \boldsymbol{k}^2_{\text{jet}} = Q^2_{\text{jet}}$

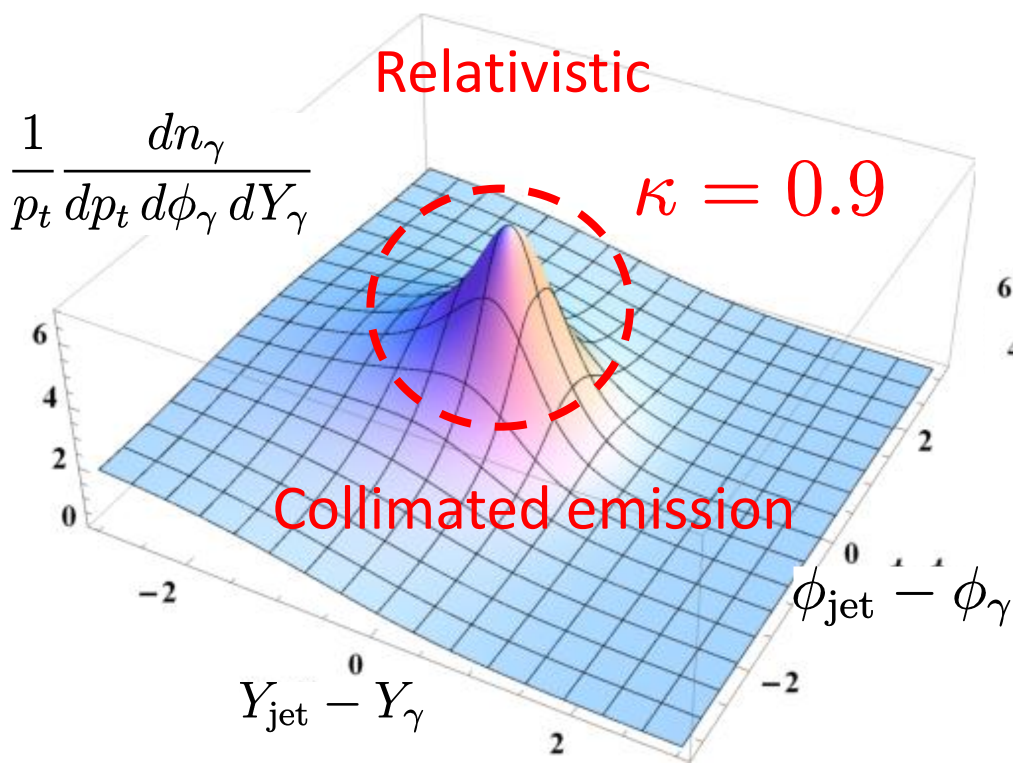
$$v_\perp = \frac{k_t}{\epsilon_{\text{jet}}} = \frac{k_t}{\sqrt{k_t^2 + Q^2_{\text{jet}}}\cosh Y_{\text{jet}}} = \frac{\kappa}{\cosh Y_{\text{jet}}} \qquad v_z = \tanh Y_{\text{jet}}$$

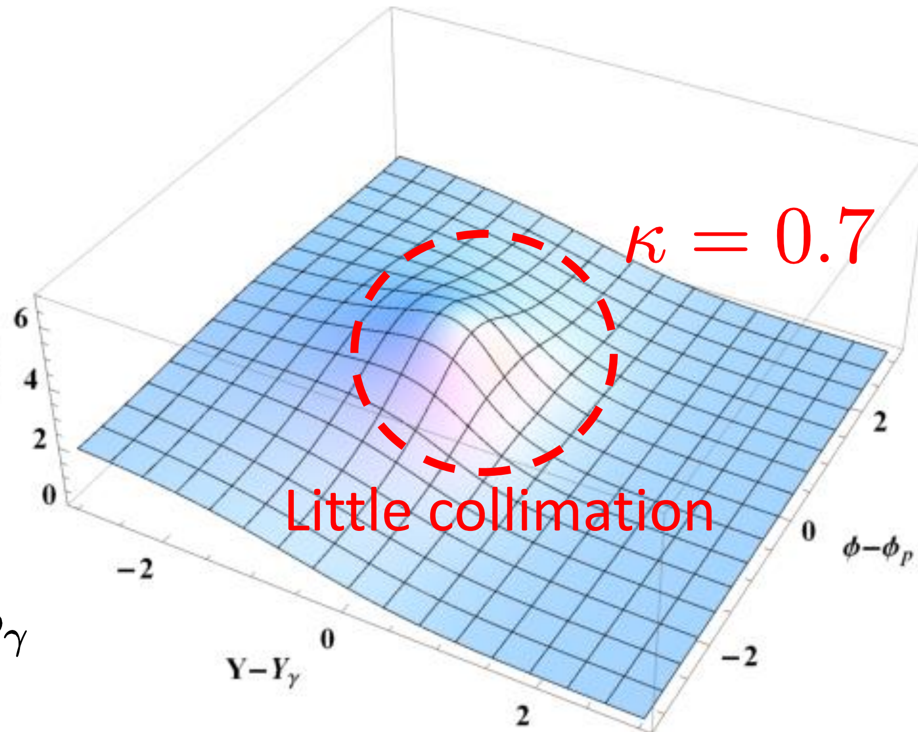
$$\kappa \begin{array}{lll} \to 1 & \text{Relativistic limit} & (k_t \gg Q_{\text{jet}}) \\ \to 0 & \text{Non}-\text{relativistic limit} & (k_t \ll Q_{\text{jet}}) \end{array}$$

Degree of the collimation in the bremsstrahlung

Photon emission rate

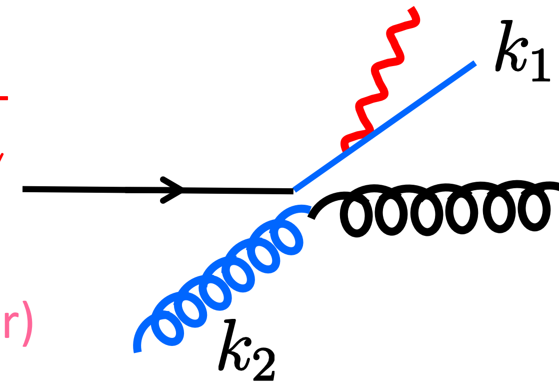
$$2\epsilon_{\boldsymbol{p}}\frac{dn_\gamma}{d^3\boldsymbol{p}} = \frac{\alpha_{\rm em}}{p_\perp^2}\frac{(\cdots)}{\{\,\cosh(Y_{\rm jet}-Y_\gamma) - \kappa\cos(\phi_{\rm jet}-\phi_\gamma)\,\}^2} \to \frac{1}{1-\kappa} \text{ when } \begin{array}{l} Y_{\rm jet} = Y_\gamma \\ \phi_{\rm jet} = \phi_\gamma \end{array}$$





Convolution of jet distribution and photon emission rate

$$\epsilon_{\boldsymbol{p}} \frac{dN_\gamma}{d^3\boldsymbol{p}} = \mathcal{N}_{\text{jet}} \int d^4k_1 \int d^4k_2 \, \frac{dn_{\text{jet}}}{d^4k_1 d^4k_2} \cdot \epsilon_{\boldsymbol{p}} \frac{dn_\gamma}{d^3\boldsymbol{p}_\gamma}$$



Overall normalization includes contributions of u, d, s, and their anti-quarks; left- and right-moving q (qbar)

-- Fitted to the LO pQCD calculation from J. Fries, et al., (2003)

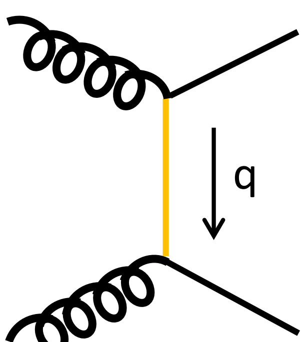
What is the dominant quark-jet production process?

→ Gluon Compton scattering

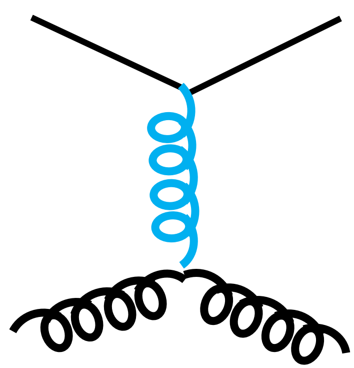
1. Gluon-dominant PDF

→ Take processes involving at least one gluon.

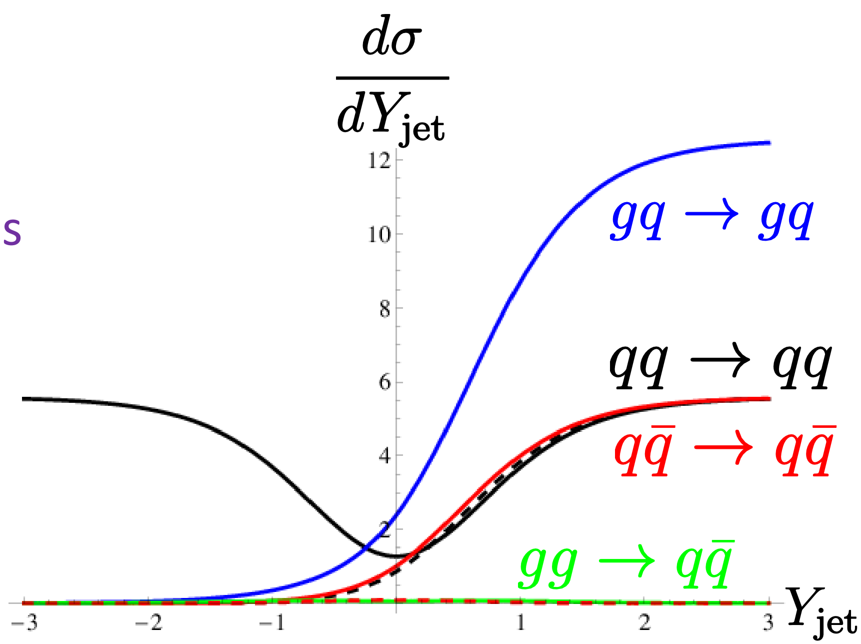
2. Dominant diagrams from gluon exchanges



Enhanced by 1/q



✔ Enhanced by 1/q²



Normalized by α_s^2/k_t^2

Transverse jet momentum distribution

Assuming the boost invariance,

$$\epsilon_{\boldsymbol{p}} \frac{dN_\gamma}{d^3\boldsymbol{p}} = \mathcal{N}_{\rm jet} \int dY_{\rm com} dY \int d\phi_{\rm jet} \int_{k_{\rm min}}^{k_{\rm max}} dk_t k_t \, \frac{dn_{\rm jet}}{k_t dk_t d\phi_{\rm jet} dY} \cdot \epsilon_{\boldsymbol{p}} \frac{dn_\gamma}{d^3\boldsymbol{p}}$$

$$Y_{\rm com} = Y_1 + Y_2$$

$$Y = (Y_1 - Y_2)/2$$

$$\frac{dn_{\rm jet}}{k_t dk_t d\phi_{\rm jet} dY} = \frac{\alpha_s^2}{k_t^2} \frac{d\sigma_{gq}}{dY} \left(\frac{1}{1 + k_t/Q_{\rm sat}} \right)^\beta \left(1 + 2 v_{\rm jet}^{(2)} \cos 2\phi_{\rm jet} + \cdots \right)$$

+ Phenomenological parameters

$\phi_{\rm jet}$ is measured from the reaction plane.

$$\beta \sim 6, \; v_{\rm jet}^{(2)} \sim v_2 \text{ of high-}p_t \, \pi^0$$

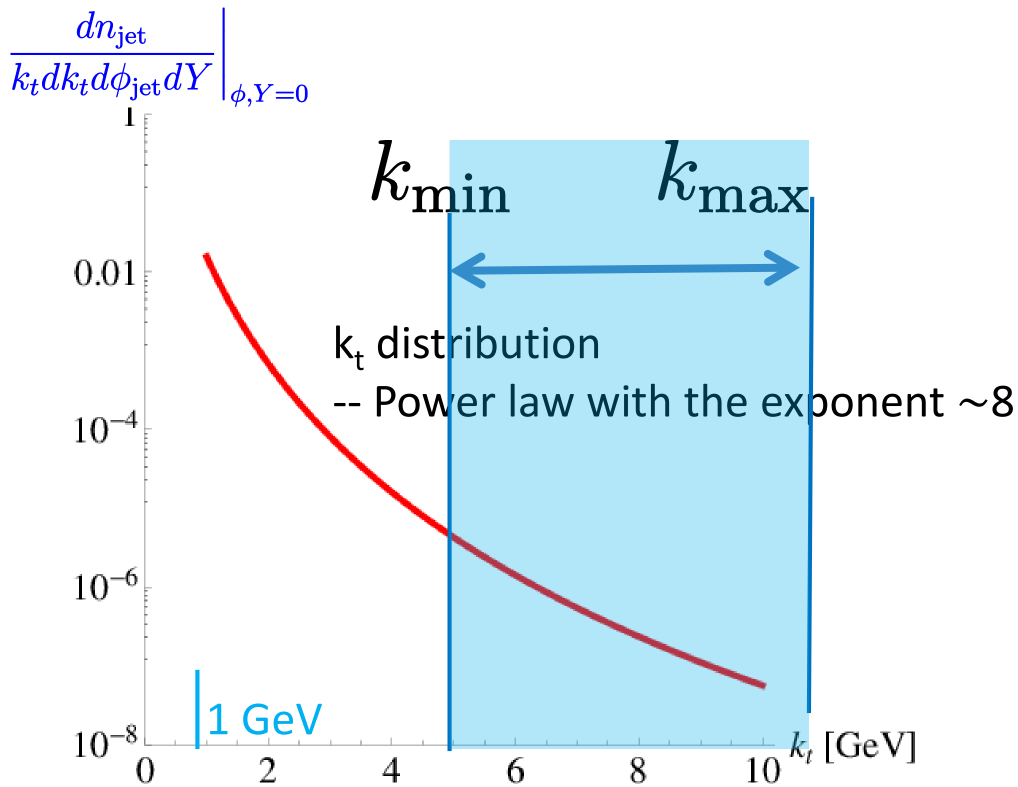
Cutoffs of the transverse jet momentum

Maximum jet momentum should be smaller than the beam energy: $s_{gq} < s_{NN}$

Minimum jet momentum should be larger than the photon momentum: $\epsilon_{\rm jet} > \epsilon_{\boldsymbol{p}_\gamma}$

If this condition allows for less 1 GeV, the momentum is cutoff sharply at 1 GeV.

Expectations for photon yield and v2



Small $k_t/Q_{\rm jet}$
- Uncollimated emission
- Large contribution

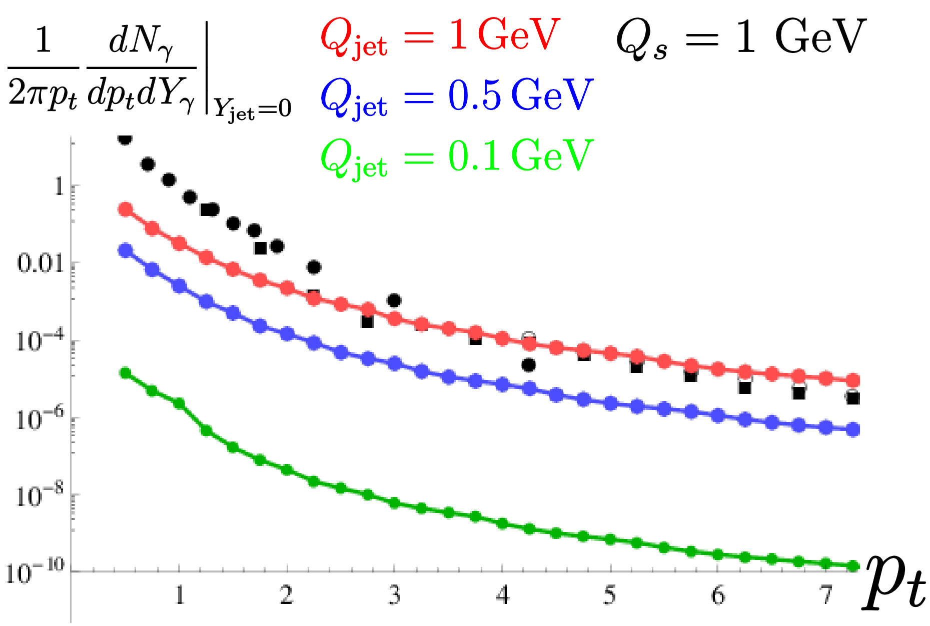
Large $k_t/Q_{\rm jet}$
- Collimated emission
- Small contribution

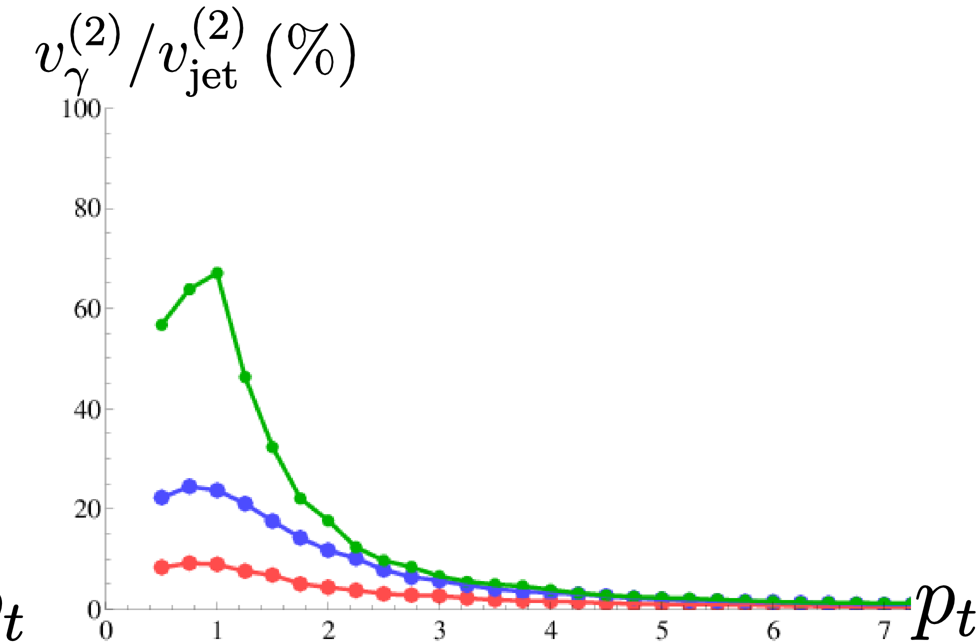
Results: RHIC energy

$$\epsilon_{\boldsymbol{p}} \frac{dN_\gamma}{d^3\boldsymbol{p}} = \frac{1}{2\pi p_t} \frac{dN_\gamma}{dp_t dY_\gamma} \left(1 + 2v_\gamma^{(2)} \cos 2\phi_p + \cdots \right)$$

Photon yield
from the jet fragmentation

Ratio of the anisotropies: $v_\gamma^{(2)} / v_{\mathrm{jet}}^{(2)}$ (%)
-- Momentum anisotropy transferred
from jets to photons.

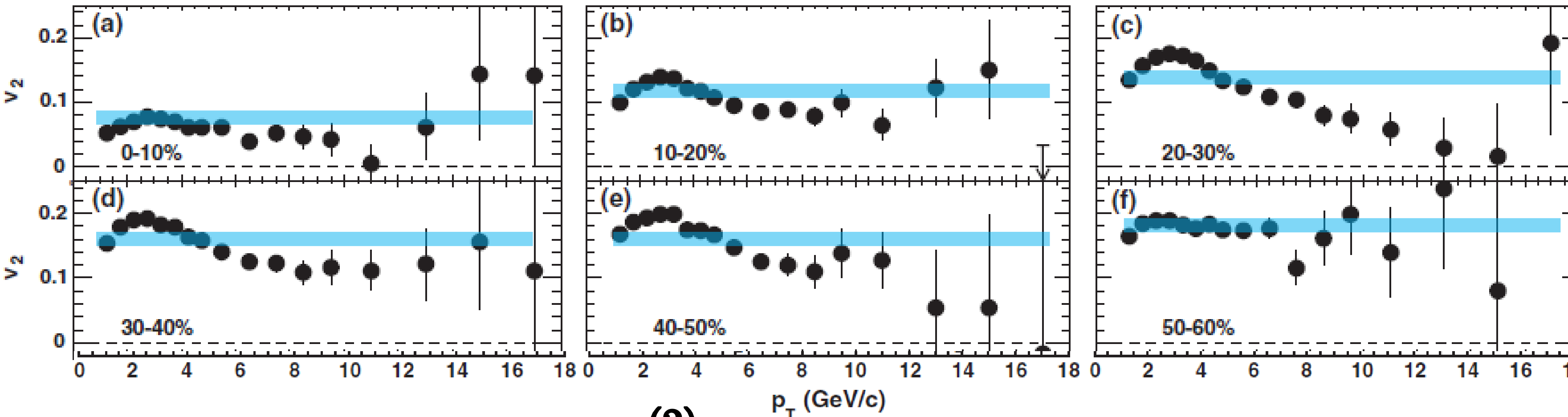




Converting the jet v_2 to the photon v_2

High p_t pion v_2

PHENIX, 2010, 2013



P_t averaged jet v_2

0-10%: 0.066

10-20%: 0.097

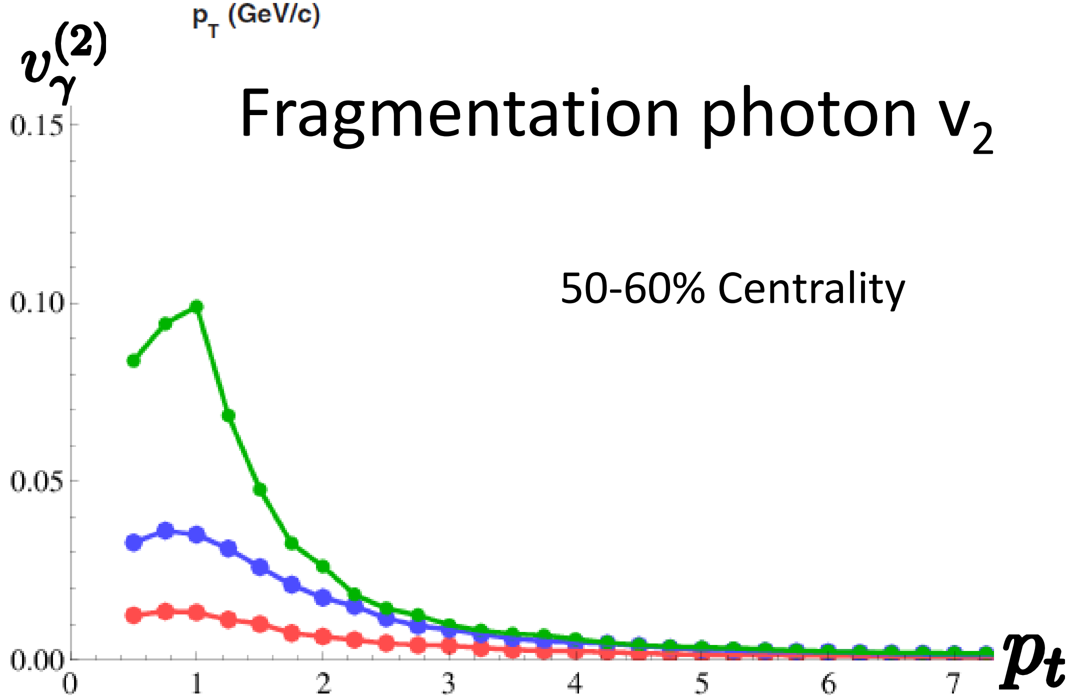
20-30%: 0.12

30-40%: 0.148

40-50%: 0.136

50-60%: 0.173

Fragmentation photon v_2



Summary

We investigated the jet fragmentation photons by the simplest and clearest setup, which captures the importance of kinematics and jet mass.

Conclusion for the first estimate:

Large v2 $\Leftrightarrow$ Small yield

Small v2 $\Leftrightarrow$ Large yield

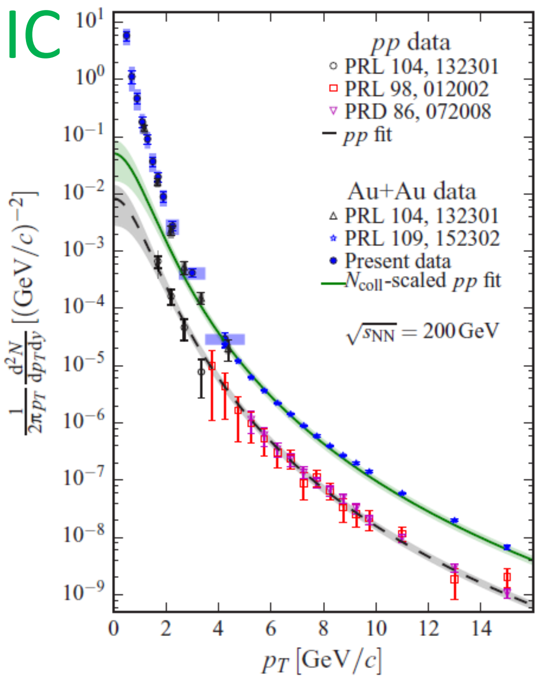
What about the medium-induced photon radiation?

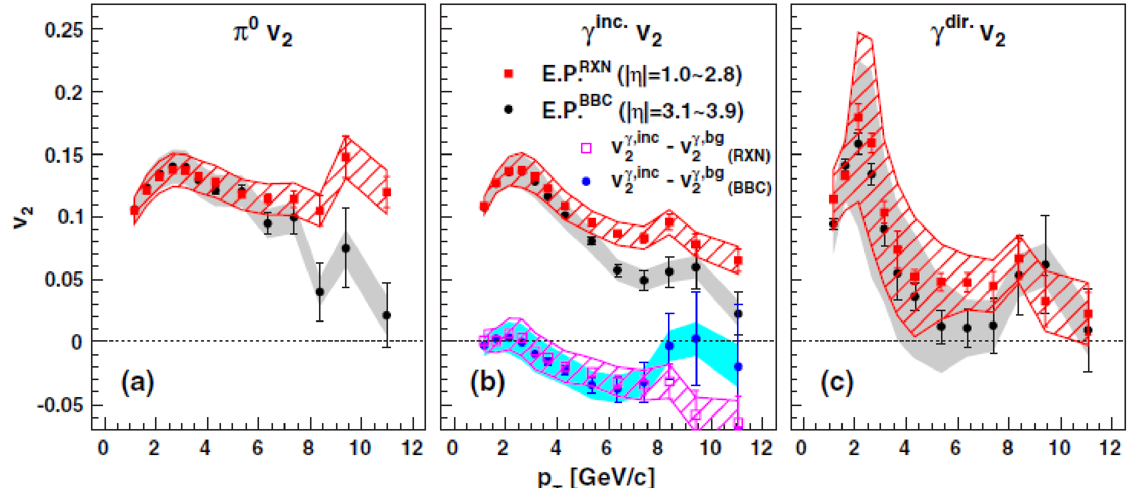
c.f., Turbide, et al.

Need to pursue mechanisms of the geometrical scaling of photons.

Recent photon measurements See next talks.

RHIC





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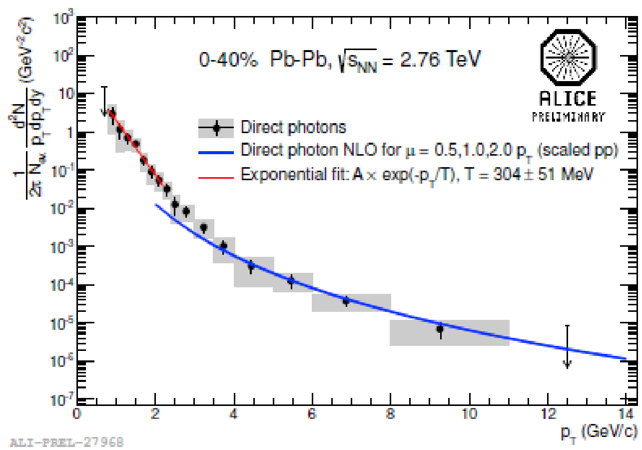
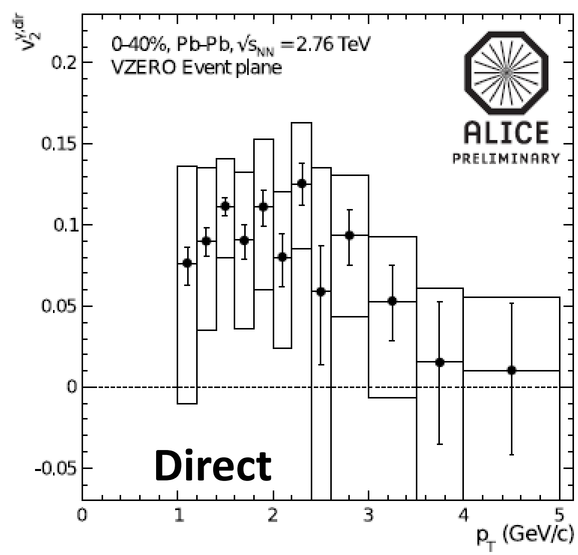
LHC





ALICE

How precisely do we know photon sources?

$$N_{\mathrm{dir}} = N_{\mathrm{prompt}} + N_{\mathrm{jet}} + N_{\mathrm{QGP}} + N_{\mathrm{Had}} + \cdots$$

Hard

Semi-hard
High T

Soft
Low T

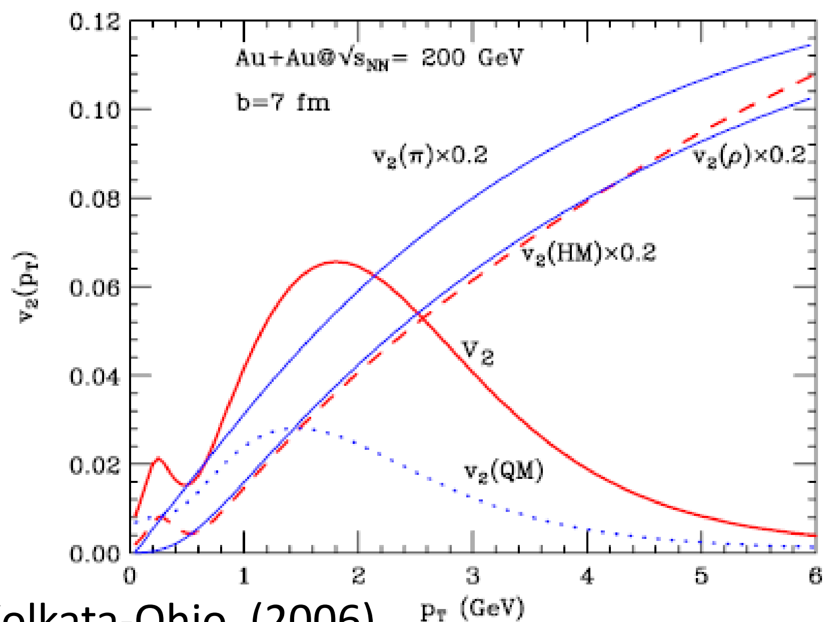
1D expansion → 3D expansion
(Transverse-flow development)

$$v_{\mathrm{dir}}^{(2)} = N_{\mathrm{prompt}} v_{\mathrm{prompt}}^{(2)} + N_{\mathrm{jet}} v_{\mathrm{jet}}^{(2)} + N_{\mathrm{QGP}} v_{\mathrm{QGP}}^{(2)} + N_{\mathrm{Had}} v_{\mathrm{Had}}^{(2)} + \cdots$$

Small ??? Small Large

Ellipsis includes other sources such as Glasma, strong B-fields, etc.

Early theoretical observations:
+ Small v2 in QGP phase
+ Large v2 in hadron phase
→ On average, small v2 of direct photons



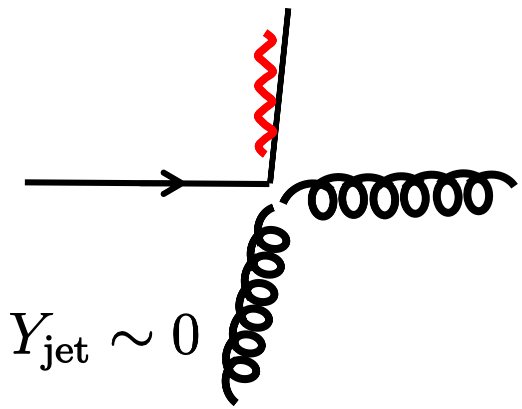
Kolkata-Ohio, (2006)
Consistent results from McGill-BNL, (2011)

$$\frac{dn_{\mathrm{jet}}}{k_t dk_t d\phi_{\mathrm{jet}} dY} = \frac{\alpha_s^2}{k_t^2}\frac{d\sigma_{gq}}{dY}\left(\frac{1}{1+k_t/Q_{\mathrm{sat}}}\right)^{\beta}\left\{1+2v_{\mathrm{jet}}^{(2)}\cos 2\phi_{\mathrm{jet}}+\cdots\right\}$$

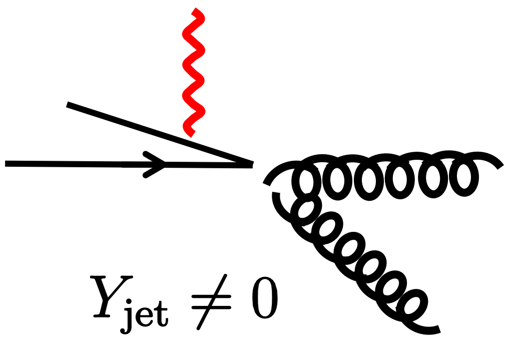
$$\epsilon_{\boldsymbol{p}}\frac{dN_\gamma}{d^3\boldsymbol{p}} = \frac{1}{2\pi p_t}\frac{dN_\gamma}{dp_t dY_\gamma}\left\{1+2v_\gamma^{(2)}\cos 2\phi_p+\cdots\right\}$$

$$\frac{v_\gamma^{(2)}}{v_{\mathrm{jet}}^{(2)}} = \frac{\int \cos(2\phi) f_0(k_t, Y)\cdot \epsilon_{\boldsymbol{p}}\frac{dn_\gamma}{d^3\boldsymbol{p}}}{\int f_0(k_t, Y)\cdot \epsilon_{\boldsymbol{p}}\frac{dn_\gamma}{d^3\boldsymbol{p}}}$$

Rapidity distribution of jets emitting photons in mid-rapidity

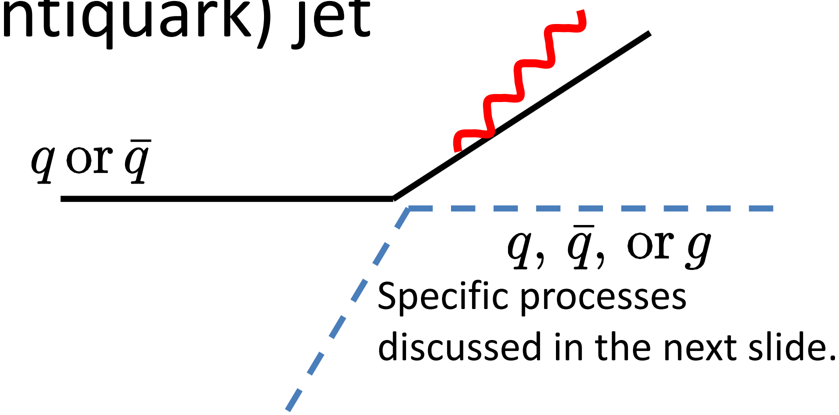


- Collimated emission



- Uncollimated emission

Bremsstrahlung from a quark (antiquark) jet



Photon emission rate from quark current

$$2\epsilon_{\boldsymbol{p}}\frac{dn_\gamma}{d^3\boldsymbol{p}} = -\frac{1}{(2\pi)^3}\,\tilde{j}^\mu(p)\tilde{j}^*_\mu(p)\Big|_{p^0=|\boldsymbol{p}|}$$

Quark (antiquark) current

$$j^\mu(x) = e\{\,v^\mu_{\rm ini}\delta^{(3)}(\boldsymbol{x}-\boldsymbol{v}_{\rm ini}t)\theta(-t) + v^\mu_{\rm fin}\delta^{(3)}(\boldsymbol{x}-\boldsymbol{v}_{\rm fin}t)\theta(t)\,\}$$

$$v_{\rm ini} = (0,0,1)$$

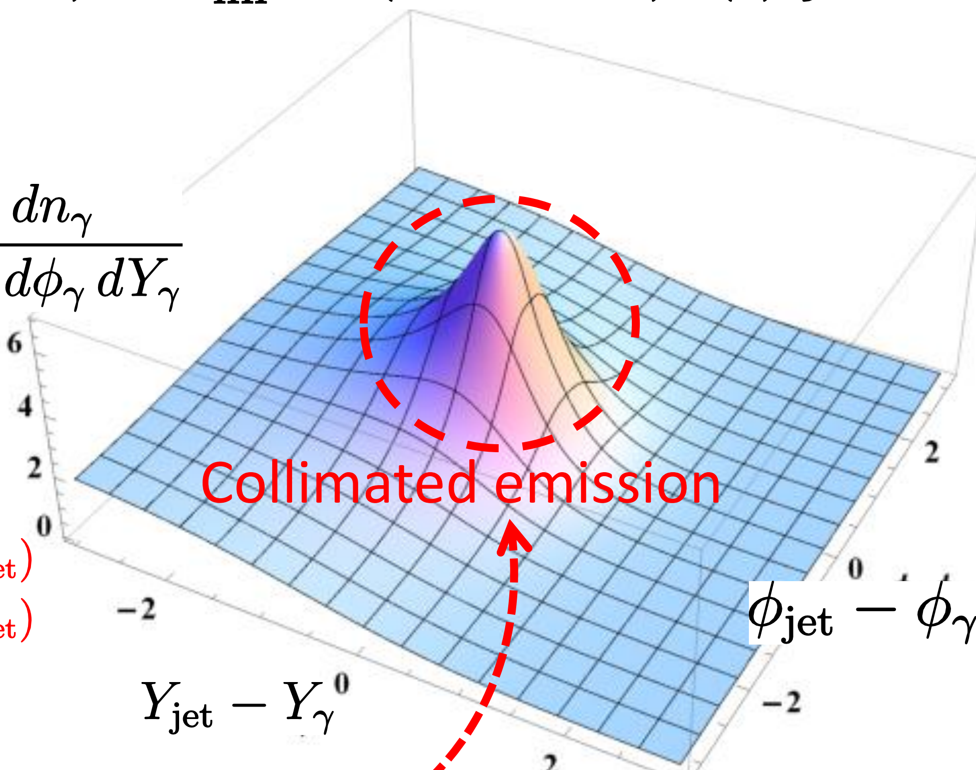
Classical trajectory after the scattering

$$\epsilon^2_{\rm jet} - \boldsymbol{k}^2_{\rm jet} = Q^2_{\rm jet}$$

$$v_\perp = \frac{k_t}{\epsilon_{\rm jet}} = \frac{k_t}{\sqrt{k_t^2+Q^2_{\rm jet}}\cosh Y_{\rm jet}}$$

$$\kappa \quad \begin{array}{lll} \to 1 & \text{Relativistic limit} & (k_t \gg Q_{\rm jet}) \\ \to 0 & \text{Non-relativistic limit} & (k_t \ll Q_{\rm jet}) \end{array}$$

$$\frac{1}{p_t}\frac{dn_\gamma}{dp_t\,d\phi_\gamma\,dY_\gamma}$$



Photon emission rate

$$2\epsilon_{\boldsymbol{p}}\frac{dn_\gamma}{d^3\boldsymbol{p}} \propto \frac{\alpha_{\rm em}}{p_\perp^2}\frac{1}{\{\cosh(Y_{\rm jet}-Y_\gamma) - \kappa\cos(\phi_{\rm jet}-\phi_\gamma)\,\}^2}$$

$$\kappa = 0.9$$

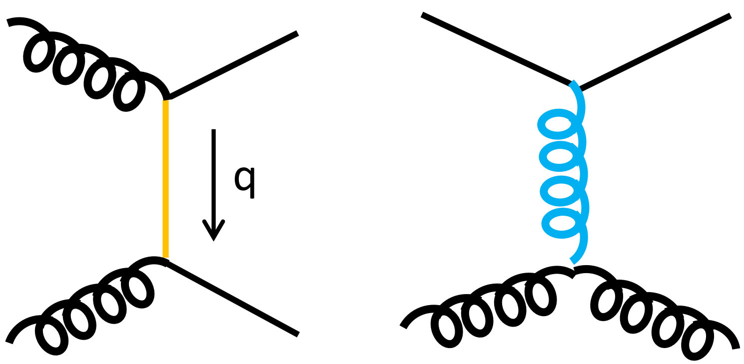
What is the dominant quark-jet production process?

→ Gluon Compton scattering

1. Gluon-dominant PDF

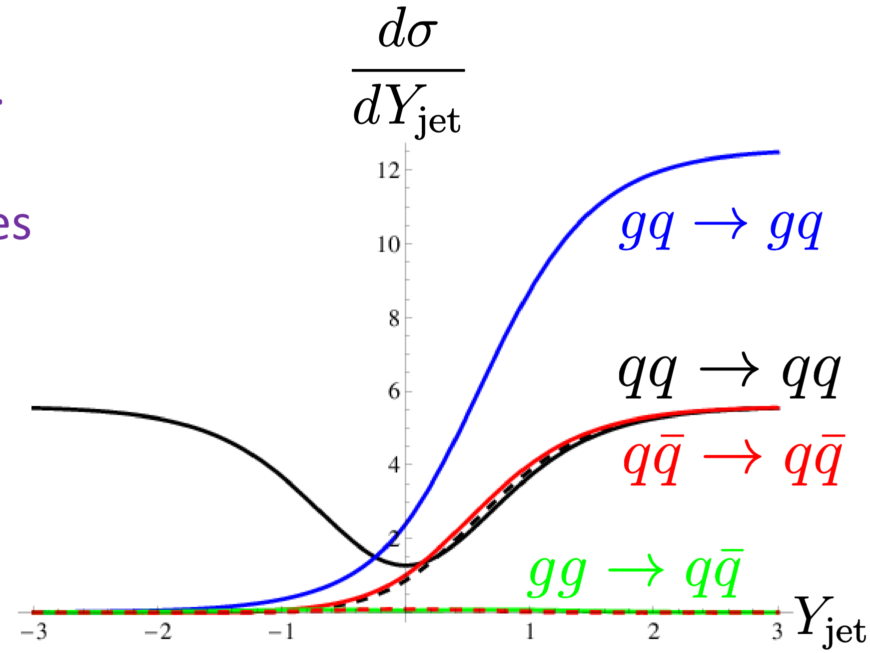
→ Take processes involving at least one gluon.

2. Dominant diagrams from gluon exchanges



Enhanced by 1/q

✔ Enhanced by $1/q^2$



Normalized by α_s^2/k_t^2

Leading-order results

$$\frac{d\sigma_{gq}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}^2}\left[-\frac{4}{9}\left(\frac{\hat{s}}{\hat{u}}+\frac{\hat{u}}{\hat{s}}\right)+\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right]$$

$$\frac{d\sigma_{gg}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}^2}\left[\frac{1}{6}\left(\frac{\hat{t}}{\hat{u}}+\frac{\hat{u}}{\hat{t}}\right)-\frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]$$

$$\begin{aligned}\hat{s} &= (2k_t\cosh Y)^2\\ \hat{t} &= -\hat{s}(1-\tanh Y)/2\\ \hat{u} &= -\hat{s}(1+\tanh Y)/2\end{aligned}$$

Suppressed by COM energy